AC 2010-1020: ANALYZING STUDENT GENERATED EVIDENCE FOR SUPPORTING DESIGN DECISIONS

Jennifer Cole, Northwestern University
Jennifer Cole is the Assistant Chair in Chemical and Biological Engineering in the Robert R. McCormick School of Engineering and Applied Science at Northwestern University. Dr. Cole’s primary teaching is in Capstone Design, and her research interest are in engineering design education.

Ann McKenna, Northwestern University
Ann McKenna is the Director of Education Improvement in the Robert R. McCormick School of Engineering and Applied Science at Northwestern University. She holds a joint appointment as Research Associate Professor in the Department of Mechanical Engineering and the School of Education and Social Policy. She also serves as co-director of the Northwestern Center for Engineering Education Research (NCEER). Dr. McKenna’s research focuses on understanding the cognitive and social processes of design teaching and learning, the role of adaptive expertise in design and innovation, and teaching approaches of engineering faculty. Dr. McKenna received her B.S. and M.S. degrees in Mechanical Engineering from Drexel University and Ph.D. in Engineering, Science and Mathematics Education from the University of California at Berkeley.
Analyzing student generated evidence for supporting design decisions

Abstract

Our work is investigating the type of knowledge students use when making decisions in the process of developing design solutions. In this paper we focus on the types of evidence students provide when presenting and choosing between various design alternatives, or when they suggest a particular design approach or solution. We are interested in seeing the extent to which students use engineering disciplinary knowledge to provide evidence for making design decisions.

The major aim of our work is to investigate the role that computational and analytical abilities play in innovation in the context of engineering design and how flexible students are in applying this knowledge when developing solutions. We are using the framework of adaptive expertise to focus our work, where the framework takes into account “efficiency” and “innovation” aspects of knowledge and learning. Using the adaptive expertise framework, with a specific focus on computational/analytical knowledge, we document the type of evidence students use when selecting possible design alternatives, appropriate models or methods of analysis, and when interpreting the results to justify their decisions.

In previous work we analyzed student design project reports from different academic years, and from different disciplines. Specifically, our data consisted of first-year and capstone design experiences. This data set enabled us to compare the nature of students’ decision making and the type of analytical knowledge used at the “bookends” of the undergraduate experience. In this work we found that student teams in capstone courses support their decisions with evidence more often than teams in the first year course. Design teams in capstone courses supported over 55% of decisions with evidence, while the first year teams supported only an average of 31% of decisions with evidence. Of the evidence we documented, students used expert sources, literature, and their disciplinary knowledge to provide reasoning for their design decisions. In addition the amount of evidence, the type of knowledge used by the teams varied by both discipline and undergraduate year.

To further study the knowledge students use in decision making, our current research efforts have focused on investigating the students’ decision making during multiple stages of the design process including “Problem Definition,” “Detail Design,” and “Design Communication.” To gain a better understanding of the factors that influence the teams’ decisions in real time, we completed a more detailed analysis for capstone design students in Biomedical Engineering. Specifically, we collected initial, midterm, and final reports to capture decision making as it evolved throughout the course.

Results from this research shed light on how students use disciplinary knowledge in the process of design, what students consider to be important technical information for design, how students make design decisions, sometimes with and without appropriate evidence to support their decisions, and finally how those decisions evolve during the period of a design course.
Introduction

The National Academy of Engineering’s report on the attributes of the Engineer of 2020 say that the engineer of the future should have strong analytical skills, practical ingenuity, creativity, good communication, business, management, and leadership skills, a strong sense of professionalism, and be a lifelong learner. The world wants to see future engineers as innovative as well as knowledgeable. The attribute of “practical ingenuity” describes future engineers as technically fluent as well as innovative. The education of the future engineer must be able to prepare engineers to approach situations flexibly and with technical expertise.

To further understand how to prepare students to have “practical ingenuity,” we are investigating how flexible students are in applying disciplinary knowledge in the process of design. Specifically, we seek to explore the role that computational and analytical abilities play in innovation in the context of engineering design education. We are investigating students’ use of knowledge when making decisions in the process of developing design solutions.

Background Literature

Our study is exploring the use of student knowledge to support design decisions as they are made throughout the engineering design process. We are interested in understanding how the type of knowledge students use to support decision making changes during various stages of the design process.

Dym and Little provide a framework for the design process. They offer a five-stage prescriptive model of the design process detailing the major activities and the design tasks associated with the activities. The model consists of Problem Definition, Conceptual Design, Preliminary Design, Detailed Design, and Design Communication stages. Similar models for the design process are presented by others. In these models, the major decision making occurs during Conceptual, Preliminary, and Detailed Design stages in the form of establishing design specifications, generating and evaluating design alternatives, and optimizing chosen design. The designers document their rationale behind design decisions throughout the design process, and organize these justifications into the written report in the Design Communication stage.

Bonnardel and Sumner describe the decision making process in design as an iterative process moving between problem-framing and problem-solving. Decision making during problem-framing consists of refining design goals and specifications, and during problem-solving, decision making occurs as solutions that are evaluated with respect to various criteria and constraints. Bonnardel states that designers refine their specifications and understanding of the problem with the results of their evaluation, thus establishing the iterative process. We seek to understand students’ decision making as it occurs during the design process, from problem-framing to problem-solving.

In particular, we are interested in analyzing the types of knowledge students use to create evidence to support their design decisions. For this study, we characterized the evidence created from the decision making process. One widely applied decision making strategy in engineering is the multi-attribute utility analysis. Grant describes this technique as consisting of the
following steps: establishing a set of alternatives and a set of attributes; analyzing the degree to which the alternatives fulfill the attributes; establishing a preference order of the attributes or assigning relative weights to attributes; and selecting the alternative that fulfills the attributes of highest preference.

One specific type of evidence in which we are interested is computational/analytical knowledge. We seek to investigate student flexibility in applying disciplinary knowledge in design decisions. We desire to understand how students develop the “practical ingenuity” attribute of the Engineer of 2020. This study uses the learning framework of adaptive expertise, where development occurs along two axes: innovation and efficiency. We specifically focus on computational/analytical knowledge in adaptive expertise (CADEX), and how students flexibly used computational knowledge in design decisions. In this study and our previous study, we document the type of evidence students do (or do not) use when selecting possible design alternatives, appropriate models or methods of analysis, and when interpreting the results to justify their decisions.

In our previous work, we analyzed final design reports from two senior capstone courses (Biomedical Engineering (BME) and Mechanical Engineering (ME)) and from an Engineering Design and Communication (EDC) course required for freshman and sophomores. We found that in the BME and ME capstone design courses, students averaged more decisions recorded per report than students in the first year EDC course. In addition, we found that students in the capstone courses were more likely to support their decisions with evidence. In the figure below, we show the results of the previous study.

Figure 1 (a): Average number of decisions made per team report for capstone BME (nine teams) and ME (four teams) courses and the EDC (ten teams) first year course. Average number of decisions supported with evidence, including CADEX specific evidence, for each course.

Figure 1 (b): The percentage of decisions supported with evidence, broken down by whether evidence is created by student team, or sought by team from other sources, such as literature, patents, or experts in the field.

When looking specifically at the type of evidence students were using, we found that the ME teams were more likely to use CADEX evidence. CADEX evidence typically occurred in the form of a calculation or series of calculations, plotting experimental data and finding a line of
best fit, or modeling. Forty percent of the decisions made by the ME teams were supported with CADEX evidence, whereas BME and EDC teams provided only 18% and 9% CADEX evidence, respectively. With the CADEX evidence, we found that the capstone teams included some sophisticated calculations, and used some of the “technical” knowledge taught in other courses in the engineering curriculum. The first year teams also included CADEX evidence, but in a much more limited way, and with much less frequency. In both cases, we considered two plausible explanations for the findings, i.e. 1) capstone students have more technical knowledge to draw from since they have had exposure to more technically sophisticated concepts and/or 2) the technical nature of the design problems are different at the different levels, therefore the nature of the evidence would be consistent with the complexity of the problem.

With respect to the first point, it is true that capstone students have a broader knowledge base upon which to draw; however, the evidence used was only a small fraction of what could have been used based on the complexity of the problem and the range of computational/analytical courses required by this stage in the students’ career. Therefore, our findings indicate that students have difficulty, regardless of the amount of exposure to technically sophisticated analysis, in recognizing when that knowledge would apply in a novel context such as design.

As for the second point, it is important to examine the nature of the problem to determine if, in fact, it would require any type of CADEX knowledge in the solution process. As would be appropriate, the level of sophistication of the design challenge did vary from first year to capstone; however, in both cases the solutions and design decisions would require a level of CADEX sophistication reasonable for the level of student. In other words, even though the first year design problems were less complex, students still struggled applying even this more basic technical knowledge to their decision making.

The results of our previous study led us to investigate whether decisions were being made during the design process that did not enter into the final report. Our current study examined decision making in the initial and midterm progress reports in addition to the final report for the BME capstone course. Again, the goals of the study are to document student use of knowledge in design decisions, particularly the flexible use of computational/analytical knowledge. We focus on characterizing the type of evidence students use to support design decisions, and documenting when decisions are made without supporting evidence. And we compare the type and amount of evidence used in design decisions from the initial progress report to the final report.

Research Method

The current work is guided by the following research questions:

- What is the nature of computational knowledge required in the process of design and innovation?
- What is the nature of the evidence used in the design decision making process?
- Do students change the nature of their evidence in the decision making process over time?

In order to investigate these questions we used a qualitative approach of analyzing student design reports to document and categorize students’ design decisions. Specifically, we coded students’
project reports for instances of when a design decision had been made. We used Beheshti’s description as a framework to help identify decisions, that is, a design decision is made from available design alternatives that have been evaluated against a set (or multiple sets) of design criteria. The results of these evaluations against design criteria are considered evidence that support or refute the choice of design alternative. For example, the passage below demonstrates a team’s design decision to pursue a certain design alternative.

According to the results, higher light intensity/source current is obtained with higher percent values of duty cycle. Since higher light intensity gain is preferred for phototherapy (e.g. AAP guidelines state that the spectral irradiance must be above $30 \mu W/cm^2/\text{nm}$ for treatment), a decision was made to not use a duty cycle circuitry.

The design criteria established by this team was to meet the American Association of Pediatrics’ guideline for spectral irradiance. The team evaluated several values of duty cycle on their circuit, and determined that the desired higher values of light intensity occurred when the duty cycle was nearer 100%. The team then made the design decision not to use a duty cycle.

For each team, we recorded instances of design decisions, along with a record of whether evidence was provided. For decisions supported by evidence, we categorized the evidence into two categories: (1) Evidence from Own Work (such as a calculation, building a model, or performing an experiment) or (2) Evidence from Other Sources (such as advice or recommendations from an expert in the field or from literature or patent searches). Of the team’s own evidence, we documented whether the evidence was of a CADEX nature (such as performing a calculation or series of calculations, plotting experimental data and finding a line of best fit, or modeling). Of the cases where students did not show evidence for a design decision, we noted the lack of evidence. To illustrate theses categories, a few examples of evidence are provided below.

**Example 1:** The following excerpt is from a BME capstone team designing defibrillator leads for use in pediatric devices. The team is making a selection of coating materials for the lead wires that would prevent surrounding tissues from hampering the movement of the wires during growth of the child.

“Endothelial seeding is the ideal solution to the tissue adherence problem. But since it is still in the developmental stage and is still incredibly inefficient, other solutions must be pursued. Our solution incorporates multiple methods to efficiently try and reduce the tissue adherence problem. First, instead of using PTFE, we have decided to use PEG (polyethylene glycol) and UHMWPE (ultra-high molecular weight polyethylene) as our base materials. To coat these materials on the lead, the process that is described in patent WO2006/135754A1 would be used. This involves laser-sintering the polyethylene to itself around the lead followed by the plasma-assisted chemical vapor deposition of PEG. This requires about 100°C temperatures – far less than the 350°C temperatures required to attach PTFE to the lead. The PEG deposition increases the hydrophilic character of the coating, forming protein- and cell-repellant clathrates with the aqueous environment in the blood…” (BME capstone design course, 2009 Winter Quarter, Pediatric Defibrillator Team)
The language cue for this decision was “we have decided to use PEG and UHMWPE as our base materials.” The evidence in this decision was the literature collected on the two alternatives: PTFE and PEG/UHMWPE. The team compared processes from patents, and reviewed literature for temperatures at which attachment of the coating would be performed. This search of literature was categorized as Evidence from Other Sources.

**Example 2:** The following section is from a Mechanical Engineering capstone design team. The team is designing an electronic skateboard capable of transporting a person at 10mph. The decision outlined below is for the selection of motor.

“Since we have a fixed gear ratio, our skateboard speed is limited by two factors: required power and torque. In order to select our motor we must use the following process:

1. Specify desired maximum speed (Vmax)
2. Calculate required power output from motor at Vmax
3. Due to ground clearance issues, gearing cannot be customized such that the motor reaches Pmax at Vmax
   - Calculate linear speed when P(rpm) = Prequired
   - Requires estimation of torque curve (derived from supplied skateboard)
   - Motor Selection based on both power and torque outputs for RPM at Vmax

Thus, the two most critical factors of our design are power and speed. These two factors are related, and by using this relationship we can predict our required power given a set speed. In order to begin the analysis, the forces of a skateboard must be analyzed. This is done using a free body diagram (Figure 2).

![Figure 2: Free Body Diagram](image_url)

The velocity we are looking at for a skateboard is parallel to the ground, and we can balance out forces along this axis in order to obtain the required motor force. In our case, the target velocity is 10 mph (from the PDS) and can use this velocity, along with the required motor force, to acquire the required motor power which was calculated to be 198W (calculation found in team’s report appendix).

An important factor in the calculation is the force of friction. In this case we used 35.6 N, which we empirically measured with a 200lb rider on smooth concrete. In order to estimate this frictional force we pushed a 200 lb person on a skateboard at a low
constant velocity (such that air resistance is negligible), and measured the required force.

While the 35.6 N force is a good estimate, it does not tell the whole story. There are two factors that play a large role in the highly variable friction force: surface, and weight. It is also important to see the full power-velocity relationship, and in order to do this Excel was used to obtain power-velocity curves for a variety of surfaces and weights.

![Figure 3: Power Requirements for Various Surfaces](image)

<table>
<thead>
<tr>
<th>Surface</th>
<th>Max. Velocity (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth Concrete</td>
<td>9</td>
</tr>
<tr>
<td>Rough Concrete</td>
<td>6.5</td>
</tr>
<tr>
<td>Carpet</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Figure 3: Power Requirements for Various Surfaces

![Figure 4: Various Rider Weights and Corresponding Power](image)

<table>
<thead>
<tr>
<th>Rider Weight (lbs)</th>
<th>Max. Velocity (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>9.8</td>
</tr>
<tr>
<td>150</td>
<td>8</td>
</tr>
<tr>
<td>200</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Figure 4: Various Rider Weights and Corresponding Power

As one can see from these charts and table, the required motor power varies significantly with surface, rider weight and velocity. Since our group would like to minimize motor
size (in order to reduce costs) we looked at the max. velocities produced by a 150 W motor.” (ME capstone design course, 2008, Electric Skateboard Team)

The evidence in this decision was Evidence from Own Work, and specifically it can be categorized as CADEX Evidence. The team created a free body diagram, measured friction, and plotted power vs. velocity for different surfaces and rider weights.

**Example 3:** The following paragraph is from the same Mechanical Engineering capstone design team.

“*One of the requirements specified in the PDS is that the design must be detachable from the skateboard deck and not induce any damage to the user’s skateboard. Since our design is compact and mounted under the board, the attachment must be compact as well. After researching various materials, 3M Duallock Velcro was found to meet these requirements, and provide a stable attachment...*” (ME capstone design course, 2008, Electric Skateboard Team)

The language cue in this decision was “3M Duallock Velcro was found to meet these requirements...”, but the team failed to provide suitable evidence for the decision. The team states they researched various materials, but the alternatives and the analysis of the alternatives “researched” failed to appear in the report or report appendices. In this instance the decision would be categorized as No Evidence Provided.

In our earlier study, the reports analyzed came from three different courses: a senior capstone design course in Biomedical Engineering (BME), a senior capstone design course in Mechanical Engineering (ME), and an Engineering Design and Communication (EDC) course, required for all engineering first and second year students. For all three courses, students are interacting with real clients to design solutions that fulfill a real need, and only the final reports were analyzed in that study.

In the senior capstone design course in BME, student grades are based on initial, midterm, and final reports and a final presentation. The initial report focuses on opportunity, market, client, impact on society, and the current methods for addressing the problem. Students are asked to generate ideas and a detailed project plan. The midterm report addresses alternative ways to achieve the objective, and students are asked to define the criteria they will use to evaluate their alternatives. The final report exhibits a single product concept and includes a summary of the market, technical feasibility, and analysis of the challenges to development, manufacture, and delivery of product. Projects in this course ranged from the development of devices such as an athletic mouth guard that works with braces or a pelvic exam simulator for medical training, to the creation of tools such as a computerized, user-directed posture correcting system. In the first study, the BME course contained nine groups of three to four students each and only the final reports were collected. In the current study, there were thirteen groups of three to four students, and initial, midterm, and final reports were collected and analyzed for decisions and supporting evidence.
Final reports in the senior capstone design course in ME were graded on students’ ability to showcase a single design concept. Projects in that course included the development of an adjustable height desk, a trim painting tool, an electric skateboard, and a wheelchair with single hand control. The course included four teams of four to five students each in the first study, and only final reports were collected and analyzed.

The EDC course final report is considered a final “proposal” where the design is “explained with sufficient detail, evidence, and reasoning to persuade the client it solves the problem in a way that fulfills the major stakeholder needs.” The projects in this course ranged from the formation of a tool for testing electronic components at high pressures, to creation of devices such as a volleyball delivery system for athletic training, to development of an awareness program for young students encountering peers with autism. Final reports from ten groups of three to four students were analyzed from the EDC course during the first study.

**Results**

The following section compares the type and amount of evidence used in design decisions from the initial to the final report.

In Figure 5 we compare two groups of BME seniors: one from 2008 that participated in our previous study in which only final reports were analyzed, and the other from our current study where all reports and progress reports are analyzed. We can see here that these two groups of seniors are not very different. While the nature of the projects changes every year, the number of decisions per report does not vary significantly. In 2008 students averaged 6.8 decisions per report and in the current study students averaged 4.1 decisions per report. The students in the current study supported 67% of their decisions with evidence and the 2008 students supported 57% of their decisions with evidence. Of this evidence, both groups had roughly one third as CADEX evidence, usually in the form of simple calculations or graphical presentation of experimental data. In addition, both groups had about 30% of their decisions supported by evidence from other sources, such as literature, patents, and advice from experts in the field.
Of particular interest to this study is seeing how students’ decision making evolves during the course. Figure 6 illustrates the change in the number of decisions made and the type of evidence used by students from the initial progress report to the final report.

We found that at the initial progress report (end of 4th week of course) students were not making design decisions. Most reports contained literature and patent reviews and other research necessary to begin formulating concepts and alternatives. This is not surprising, given that the instructions provided in the course syllabus stated that this initial report should contain an analysis of market, client, and problem, and did not specifically require any discussion of the
design ideas or evaluation criteria. At the midterm report (beginning of week 8) students were averaging 1.9 decisions per team, and at the final report students had increased to an average of 4.1 decisions per team. Of the decisions students made on the final reports, an average of 1.3 of the midterm decisions (67% of the midterm decisions) were repeated on the final report. Of those decisions repeated in the final report, the evidence was unchanged from the midterm on 78% of those decisions.

We noted that students were more likely to support their design decisions with CADEX evidence in the final report, changing from 4% of decisions supported in the midterm progress report to 26% of decisions in the final report. We noticed that for most students, the midterm report provided an opportunity to discuss the alternative concepts that they planned to evaluate. Most of the evidence was in the form of literature searches, client interviews, and expert sources. In the final report students’ evidence was provided as knowledge transferred from prior courses in calculations and as plots and calculations stemming from the students’ observations and experiments.

![Figure 7: Percentages of decisions supported with evidence and the type of evidence used in initial, midterm, and final reports.](image)

The type of evidence provided is broken down in Figure 7, above, to show the percent of evidence created by the students and the percent of evidence sought by the students from outside sources. We see that from the midterm to the final students are relying less on evidence from other sources (literature, patents, and experts in the field) and using their own evidence (calculations, experiments, observations).

**Summary and Future Work**

From our previous work (seen in Figure 1) we found that design teams in the capstone courses offer a higher number of decisions per report than the teams in the first year course. Furthermore, teams in capstone courses supported their decisions with evidence more often than teams in the
first year course, (over 55% of decisions supported with evidence in capstone courses, while the first year teams supported only an average of 31% of decisions with evidence).

In our current study, we took an in depth look at the Biomedical Engineering capstone course. We found that between the two studies the BME capstone teams had small differences (±2) in the number of decisions per report and amount of supporting evidence provided (as seen in Figure 5, but this could be due to the varying nature of the report topics. We found that both groups of students supported over 55% of the decisions with evidence, and of that evidence roughly one-third was CADEX evidence.

Figures 6 and 7 illustrated the change in the number of decisions made and the type of evidence used by students from the initial progress report to the final report. Students doubled the number of decisions made between the midterm to the final report, and were more likely to support their design decisions with CADEX evidence in the final report. At the beginning stages of the design process students were more likely to support their choices with information they gathered from literature and expert sources, and this was reflected in the evidence provided in the midterm progress reports. In the final report, students’ evidence was provided as knowledge transferred from prior courses in calculations and as plots and calculations stemming from the students’ observations and experiments. By the end of the course, students were equally as likely to rely on their own work or seek out the work of others to support their choices.

To further study the knowledge students use in decision making, we would like to repeat this process for the Mechanical Engineering and first year Engineering Design and Communication courses. We would like to further investigate the students’ decision making during all the stages of the design process, from Problem Definition to Design Communication, from all levels of undergraduate education.

Acknowledgements

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Bibliography