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Evaluating the Implementation of Design Heuristic Cards in an Industry Sponsored Capstone Design Course

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Abstract

Using Design Heuristics to Develop Concept Generation Skills in an Industry Sponsored Capstone Design Course Concept generation is a key skill for success in capstone design courses. Yet, this skill is rarely emphasized in traditional design courses. The present study investigates the introduction of Design Heuristics to facilitate expanded concept generation in an applied setting, a capstone design course in mechanical engineering charged with developing real-world projects for paying industry clients.Design Heuristics are cognitive prompts that enable exploration of the design space during concept generation. There are 77 Design Heuristics strategies, validated by research, and represented on a separate card in a deck. Each card includes a description of the heuristic, an abstract image depicting the application of the heuristic, and two product sketches showing how the heuristic is evident in existing consumer products. In this study, we explored design teams' use of the Design Heuristics as well as the success of teams during concept generation as a whole.Participants in the study were 120 upper division students enrolled in a year-long, team-based,industry-sponsored capstone design course in mechanical engineering. Students developed projects for industry clients with support from faculty Project Directors. Students were trained on applying the Design Heuristic cards during class. Feedback on the Design Heuristics cards was collected and concept generation progress was assessed via pre, mid, and post surveys of students, Industry Clients, and Faculty Directors.Considering the success of concept generation as a whole, results from triangulated ratings indicated that clients, faculty, and students expressed satisfaction for the concept generation phase of the project at the end of the year with regards to the quantity (combined mean = 3.91/5),creativity (combined mean = 3.90/5), and diversity of ideas (combined mean = 3.93/5) generated within the teams. One faculty director commented, "It would be difficult to improve their final product. They had an incredible array of ideas and were able to implement most of them." With regards to Design Heuristics, one student commented, "Design Heuristics was a really interesting facet of the project. This was really fun and if it could be expanded that would be helpful,however, with limited time it seemed to be balanced well."Suggestions for improvement in concept generation focused on generating an even wider range of ideas. One Faculty Director commented, "They seemed a little hesitant to throw out ideas or they would rally behind a single idea versus a brainstorm. They seemed like they wanted an answer versus a list of options." One industry client wished the team would have, "come up with at least 5 ideas that the company mentor and customer had not thought of." Similarly, one student team member suggested the team should have, "thought outside of the box more,considered wilder ideas prior to latching on to a design path." Further tips for thinking outside the box included more research, less defensiveness around personal preferences for ideas, and more time using Design Heuristics. Additional results and conclusions will be discussed in the paper.

Disciplines

Industrial and Product Design

Comments

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Evaluating the Implementation of Design Heuristic Cards in an Industry Sponsored Capstone Design Course

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Evaluating the Implementation of Design Heuristic Cards in an Industry Sponsored Capstone Design Course

Introduction

The ability to formulate numerous unique alternatives in concept generation is the underpinning foundation of design innovations [1-2]. Without adequate concept generation, one could posit that product realization could fail or be severely weakened. Encouraging undergraduate engineering students to generate multiple and diverse ideas, and facilitating an environment for it, are considered best practices for design education, yet many engineering courses and instructors lack curricula and tools to teach students specific ways to accomplish successful ideation [3-5]. This is especially challenging for engineering capstone design courses, which are crucial transitions to professional practice for engineering students, as they create simulations of the real world challenges. In capstone courses today, problems are more open-ended than they were before, students are given more freedom and flexibility in their design processes, and, in many cases, students interface with professional clients and make decisions without the instructor [6]. So, generating increasingly diverse initial design ideas becomes more important for these courses, and if the students do not have specific tools for generating ideas, they are more likely to pursue their first obvious idea, creating a higher chance for failure and a lack of innovation [7-10].

Brainstorming is by far the most familiar and widespread strategy taught throughout engineering design education, as it encourages "wild" ideas to emerge [11], with a premise of potential creative design solutions. The challenge with brainstorming is that it still leaves students without a specific way to come up with ideas; instead, the procedure allows natural ideas to emerge more freely, which can lead to team dominance issues or a paucity of ideas. Another method, *brainwriting*, [12] facilitates the flow of ideas; *analogical thinking* [13] and *morphological analysis* [14] stimulate the formation of an initial idea; and *SCAMPER* [15] and *TRIZ* [16] are used for transforming ideas into more or better ideas. Although these methods (and many others) exist to assist in concept elicitation and have been tested to varying degrees, most of them lack both empirical derivation and validation studies.

One ideation tool, designed specifically for product design, based on research, and also validated by experimental studies, is the *Design Heuristics* approach [17-21]. Design Heuristics are prompts that facilitate and guide design space exploration during concept generation by helping designers initiate new ideas from scratch or transform existing ideas into new solutions. A single Design Heuristic can produce a variety of designs, depending on how it is applied within a problem. The Design Heuristics were developed through protocol studies with expert industrial and engineering designers [18, 22] and analyses of creative products [23], and were converted into 77 cards, with each heuristic represented on a single card with examples.

For this study, Design Heuristics were incorporated into a year-long mechanical engineering capstone design course, and students had open access to the 77 Cards representing Design

Heuristics for the entire year of their projects. Formal training was implemented in the capstone design course as a strategy to introduce concept generation and the 77 Design Heuristic cards. Our work explores the use of the 77 Design Heuristic cards by the capstone design teams, including their reactions to these strategies and how they, and their advisors, believed these strategies impacted their approaches to concept generation and the resulting project outcomes. Lastly, we address the implications of applying the 77 Design Heuristic cards in an industry-sponsored capstone design context and make suggestions for future improvements.

Background

Within this section, we briefly highlight literature on capstone design, specifically its history and traditions, its role in engineering education and connection to ABET criteria, and common instructional techniques. Additionally, we describe the role of concept generation in the capstone experience, review the research that led to the development of the Design Heuristics strategies, and research on the impact of the tool on student designers and design practitioners.

Senior Capstone Design

Capstone design has been identified as a "culminating" experience for undergraduate engineering students [24]. Though these courses have gained popularity in the last 20 years, the implementation of Capstone Design courses varies greatly across engineering programs [25-26]. Course duration, project context, and the source of the project (i.e., industry, faculty research, student competitions) are dependent on the engineering domain, and the individual institution.

In the eyes of the ABET, there is a "unique importance of capstone design relative to ABET accreditation, as this course is in position to determine a program's compliance with many ABET criteria" [27]. The result is that several engineering programs rely on their capstone design course as evidence to support that their program is meeting ABET outcomes A through K [25, 28-29].

Engineering programs strategically locate capstone design courses within the last year of undergraduate engineering studies, where students can apply the fundamental technical knowledge gained in previous courses in an authentic real-world context. Several institutions have identified Capstone Design as an ideal place for teaching professional skills, which are typically not emphasized earlier in the curriculum [30]. Howe's Capstone Design survey of 232 engineering institutions showed that the five most common topics taught were: written communication, oral communication, engineering ethics, project planning and scheduling, and decision making. Only 48% of the survey respondents selected that they were teaching drawing, creativity, or concept generation [26].

We point toward Howe's survey that concept generation receives less attention than some course elements in most Capstone Design courses. As described by Muci-Küchler, Weaver and Dolan [31]:

> *"[I]t is not uncommon for students to conceive and focus on a couple of solution concepts as soon as the requirements have been identified, quickly select one of them, and proceed to the detailed design stage of the chosen concept. The problem is that if an*

inherently weak concept has been selected, even flawless execution of all the remaining steps in the product development process results in a poor and uncompetitive end result."

Though concept generation is a critical portion to the success of engineering design, few studies have highlighted the impact of focused concept generation instruction and the outcomes of the application.

The Design Heuristics Approach to Concept Generation

The term "heuristic" has commonly referred to a strategy that uses readily accessible information to control problem-solving processes [32]. These strategies do not guarantee reaching the best solution (or even reaching any solution) but provide an efficient method to reach a solution, a type of cognitive shortcut. The definition of Design Heuristics builds on the definition of heuristics, by helping designers reach design solutions more efficiently [18, 22-23, 33].

The Design Heuristics were derived from a case study of an industrial designer, a review of award-winning products, and a protocol study of student and practicing engineers and industrial designers [18, 22-23, 33-37]. These studies culminated in an accumulated collection of 77 Design Heuristics, and each of these strategies were presented on a card that represented how the strategy could be applied as well as existing examples of application. Design Heuristics instructional resources and examples of the 77 cards are included on the Design Heuristics website [38].

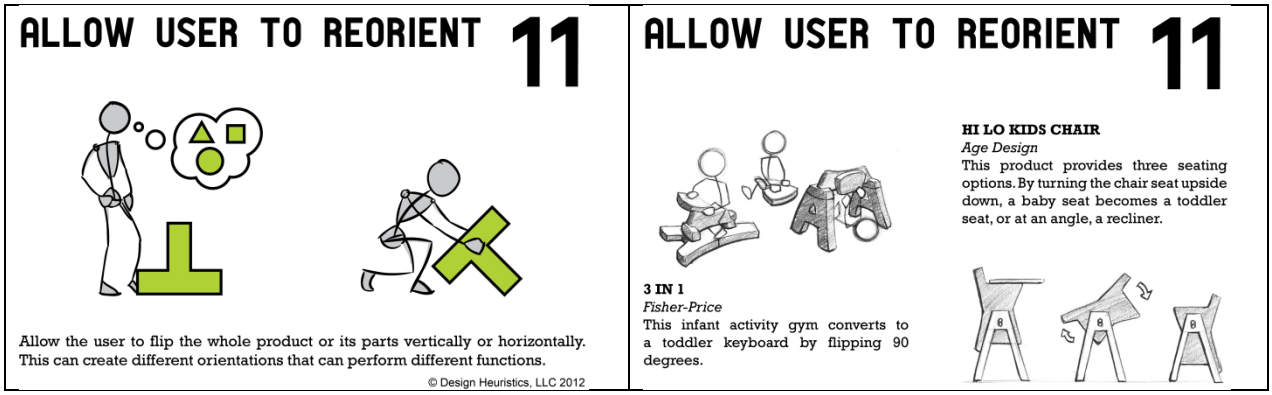

Figure 1. Example Design Heuristic Card

The 77 cards representing the Design Heuristics have been empirically tested in classrooms and with practicing engineers [17, 19-21, 39-41]. These studies confirmed that the Design Heuristics were useful in guiding engineering and design students and experts to develop less obvious and more creative solutions, identify new design opportunities, and transform ideas into more original ones. Additionally, the studies provide support that this approach to helping students systematically approach idea generation is successful with students from introductory courses through capstone course and graduate design courses [17, 39-40]. Based on the existing research, this tool was chosen to incorporate into a full-year capstone course, where students were constrained by industry-sponsored project descriptions and deliverables.

Setting for Research

University of Colorado, Mechanical Engineering Capstone Design Course Structure

At the University of Colorado, the Design Center (DC) Colorado serves as the umbrella organization for the mechanical engineering Senior Capstone Design (SCD) course. DC Colorado is an industry-education partnership within the Department of Mechanical Engineering (ME) at the University of Colorado. The Center functions as a small consulting business within the department—overseeing design facilities, staff, and maintaining an operational budget through client-sponsored student design projects.

Sponsored design projects are the foundation of the yearlong SCD course, where the DC Colorado business setting is used as the organizational structure for the SCD course (see Figure 2). Each five-person student team works closely with the sponsoring companies to refine the final project scope (based on an original client generated project need); develop design alternatives; and manufacture, assemble and test products to meet client specification. Organizationally, the DC Colorado Director for Undergraduate Design Programs coordinates the SCD course. Each student team is advised by a ME faculty member (Project Director), with the Industry Mentors representing the sponsoring company and serving as the client. The Senior Capstone Design high-level course objectives include:

- Developing an understanding of the necessary professional skills needed to succeed in industry
- Understanding how to collaboratively work in a team toward a common design
- Becoming adept at written technical communications, oral technical communications, and managing long term projects
- Becoming proficient at integrating technical skills into the design process

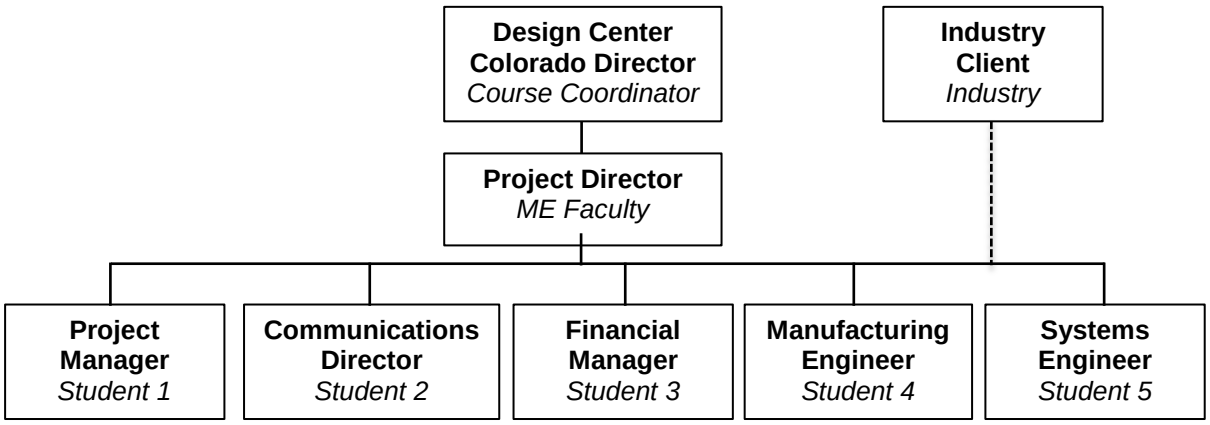

Figure 2: Senior Capstone Design corporate structure, simulating industry work environment

Specific training sessions are held for SCD students to develop skills in concept generation, project management, team dynamics, engineering print creation for manufacturing, and technical writing. During this year-long study, 118 mechanical engineering students grouped in 24 teams took the SCD course.

Research Questions and Method

For this study, we seek to understand the impact of implementing the 77 Design Heuristics cards in an industry-sponsored capstone design course. Specifically, we investigated the following research questions:

1. How do Senior Capstone Design students perceive targeted concept generation training?
2. How did the teams choose to implement the 77 Design Heuristic cards during the year-long industry sponsored design project?
3. What is the impact of using the 77 Design Heuristics cards on Senior Capstone Design course and project outcomes?

In this paper, we focus on the results of our pre-post surveys with students, clients, and instructors. Pre-post student surveys with self-ratings of concept generation skills and feedback on training were administered to all Senior Capstone Design students in the fall of 2012 and spring of 2013. A combination of Likert-type questions and open-ended questions were asked on the survey. A total of 108 students responded to the pre-survey out of 118, and 103 responded to the post-survey. A follow-up survey was administered in fall 2013, the semester after students completed the SCD course, asking student teams to rate the frequency of use of the 77 Design Heuristics cards.

Skill development in design courses is typically measured via student self-reported data. While these data are easy to obtain and have been found to provide valid results, criticisms have been leveled at self-reported student data as a standalone evaluation of student skills [42]. These criticisms target the bias inherent in the limited experiences of a 22-year-old student evaluating their own professional development. One alternative to reduce the bias associated with self-reported student ratings is to implement triangulated assessment methods where three parties (student, Faculty Advisor, and Industry Mentor) measure the same set of skills to provide a broader perspective on student development.

Concept Generation Training

The concept generation training took place during four class periods. A 60-minute introduction session was held during the third week in the fall semester. This session focused on introducing concept generation, Design Heuristic strategies, and the 77 Design Heuristic cards. Each student team was provided a deck of 77 Design Heuristic cards that the team would keep for the academic year. Concept Generation Handouts were used during the session, which prompted students to provide a drawing and written description of the concept, and asked them to identify the Design Heuristic used. During this introduction session, students completed two practice design scenarios (presented by the instructors) on their own and shared their concepts with a neighboring student.

During the same week, a second training session was held for 75-minutes with student teams practicing with the 77 Design Heuristic cards and Concept Generation Handouts on a more advanced design scenario. 65 minutes of this session were dedicated to generating concepts to solve the presented engineering challenge. Students were asked to choose their top two designs

and share with their team members during the final 10 minutes.

The third training session commenced during the fifth week of the fall semester, after the student teams had been paired with their industry sponsor and were familiar with their project description. The focus of the third session was to use the 77 Design Heuristic cards and the Concept Generation Handouts to produce multiple, unique solutions to their assigned industry project. The fourth and final training session took place during the second week of spring semester. Student teams were re-introduced to concept generation in the context of product design iteration. Many student teams are faced with redesigning a critical part of their prototype after the formal design reviews with Project Directors and Industry Clients. The 77 Design Heuristic cards were used during this session as a method to push design solutions outside of the obvious and into the innovative space.

Results

The results we present in this section focus on: (1) the impact of the design heuristic training on concept generation; (2) the use of the Design Heuristics cards for the design project; and (3) the impact of the use of the cards on the outcomes of the Capstone Design course and project. The data were analyzed with SPSS statistical software. Table 1 displays the survey questions that were administered for each research question. Data for each research question are reviewed in subsequent sub-sections.

Table 1: Research Questions and Associated Survey Questions

Research Question: How do Senior Capstone Design students perceive targeted concept generation training?
How interested are you in learning strategies to generate ideas? (scale: 1-7, 1=not at all interested, 7=very interested)
How important is it to have a variety of ideas to explore during idea generation? (scale: 1-7, 1=not at all important 7=very important)
How helpful for your project was the in-class Design Heuristics training? (scale: 1-5, 1= very unhelpful and 5 = very helpful) Please Comment (scale: open-ended)
Do you think additional in-class Design Heuristics training would be helpful during the second semester? (scale: yes/no)
Research Question: How did the teams choose to implement the 77 Design Heuristic cards during the year-long industry sponsored design project?
How often did you use the Design Heuristic cards to generate ideas for your project? (Scale: 1-5, 1= 1 time and 5 = Greater than 10 times) Please Comment (scale: open-ended)
Did you use the cards more in the fall or spring semester? (scale: fall/spring)
Research Question: What is the impact of utilizing the 77 Design Heuristics cards on Senior Capstone Design course and project outcomes?
How important is it to have a variety of ideas to explore during idea generation? (scale: 1-7, 1=not at all important 7=very important)

Which of the following scenarios during the idea generation phase are you more comfortable with (check one): (scale choice 1: spending all of your time on one developed idea that you will take to a client) (scale choice 2: spending the same amount of time on generating multiple less developed ideas to take a client) Please comment (scale: open-ended)
List three strategies you used when generating ideas for your project. (scale: open-ended)
Rate your team's quantity of ideas generated for this project. (scale: 1-5, 1= miserable and 5 = delightful) Please Comment (scale: open-ended)
Rate your team's creativity of ideas generated for this project. (scale: 1-5, 1= miserable and 5 = delightful) Please Comment (scale: open-ended)
Rate your team's diversity (i.e. unique designs) of ideas generated for this project. (scale: 1-5, 1= miserable and 5 = delightful) Please Comment (scale: open-ended)
What guided your team when making your final design selection? Check all that Apply: (scale choices: time; Faculty Director, Industry Client) Which was most influential in making your selection? (scale: open-ended)

Design Heuristic Training

The first research question targeted the impact of the in-class Design Heuristics training. Table 2 presents the student survey results. To establish initial interest before the Design Heuristics training, students were asked to rate their interest in learning new concept generation techniques. Students reported a high degree of interest in learning strategies to generate ideas before training commenced (mean 6.15/7.0). Additionally, students felt that it was important to be able to have several ideas during concept generation (mean 6.80/7.0) before the training. Post-surveys indicated that students found the training moderately helpful (mean = 3.33/5.0) for their projects. However, the majority (73%) of students did not feel the need for additional in-class training in the second semester.

Table 2: Design Heuristic Training Questions

Survey Item	**Student Response**
1. How interested are you in learning strategies to generate ideas?	6.15 / 7.0
2. How important is it to have a variety of ideas to explore during idea generation?	6.80 / 7.0
3. How helpful for your project was the in-class Design Heuristics training?	3.33 / 5.0
4. Do you think additional in-class Design Heuristics training would be helpful during the second semester?	73% No

When asked to explain their ratings for survey item 3 in Table 2, the main benefit of the Design Heuristics was that using Design Heuristics allowed them to "*jump start the project*" and "*get the project rolling*" through a novel method of concept generation. Additional statements when

asked to explain their reasoning for the rating of "how helpful for your project was the in-class Design Heuristics training" included:

> *"We don't get many opportunities to think outside the box for earlier classes so our brains aren't geared towards this type of thinking."*

> *"I feel like the cards were helpful for brainstorming ideas and worked well in changing the way you think."*

Implementation of 77 Design Heuristics Cards During Design Process

The second research question investigated the implementation of the Design Heuristics cards in the design project. The majority of students indicated that they used the cards infrequently outside of the class sessions for their project (mean = 1.73/5), either one time per semester (36%) or two to four times (50%) with all students claiming they used the cards more in the fall than the spring (see Table 3).

Table 3: Design Heuristic Implementation

Survey Item	**Student Response**
1. How often did you use the Design Heuristic cards to generate ideas for your project?	1.73 / 5.0
2. Did you use the cards more in the fall or spring semester?	100% Fall

When asked to comment on how often they used the Design Heuristic cards to generate ideas, student responses indicated some difficulty putting the training into practice for the project.

> *"We didn't sit down with the cards to redesign once we came up with our initial design. That is where things would need to change, actually getting the students in their teams with their faculty mentor to go over useful designs. Extra classroom time outside initial intro isn't very effective."*

Others echoed this comment,

> *"When second semester comes around, it should be up to each individual team to go back to the cards, if necessary - it would be a waste of time for many others."*

> *"They were good for hitting home on the fact that we should brainstorm - A LOT - before deciding on the path to take for the project, but we never actually looked through the cards when brainstorming."*

Students seemed to feel that concept generation happened only at the beginning of design and once they had developed multiple ideas early on, it was not useful or practical to "go back" to concept generation later in their design processes.

Course Outcomes

The third research question turns to the outcomes of the course in terms of attitudes, strategies and performance with respect to concept generation. In response to the following question, "how important is it to have a variety of ideas to explore during idea generation," (1-7 scale, 7 = very

important) student team members indicated in both pre- (mean = 6.72/7.0) and post-assessment (mean = 6.78/7.0; $p > .05$) that it was important to them to have a variety of ideas to explore during concept generation. Another question targeting student attitudes asked whether students were more comfortable spending all of their time on developing a single idea for a client or bringing multiple less developed ideas to a client. Results indicated that 81% preferred developing multiple less-developed ideas. One student commented:

> *"Regarding initial design of most prototypes, it's important to provide options for the client to help gain a better perspective on the client's needs, which also gives the client more freedom to decide what they would like in their product. After this initial idea generation, it is then best to work on narrowing down those ideas to match the client's needs."*

Students were posed the following question about design strategies, "list three strategies you used when generating ideas for your project." Student written responses were coded and are displayed in Table 4. When asked about strategies used for generating ideas, students reported several common strategies on both the pre- and post-assessments, including redefine the problem statement, research similar ideas/existing designs, and collaborate/discuss with others. Two strategies emerged on the post-test that were not present in the pre-test: consider need/functionality and use Design Heuristics cards, indicating some growth in strategies across the year.

Table 4: Themes for Student Generated Design Strategies

Pre Survey – Fall 2012	Post Survey – Spring 2013
1. Look at existing designs/solutions	1. Redefine problem statement
2. Lay out project goals	2. Research similar ideas/existing designs
3. Collaborate/discuss with people	3. Individual brainstorm
4. Research related ideas	4. Group brainstorm
5. Sketch ideas	5. Consider need and functionality
6. Think outside of the box	6. Visualize
7. Identify the problem	7. Use Design Heuristic cards
8. Brainstorm	

Table 5 presents the results from triangulated ratings of concept generation. Considering concept generation performance, end of the year results from triangulated ratings indicated that clients, faculty, and students expressed satisfaction, with some room for improvement, for the concept generation phase of the project in regards to the quantity (combined mean = 3.91/5.0), creativity (combined mean = 3.90/5.0), and diversity of ideas (combined mean = 3.93/5.0) generated within the teams.

Table 5: Triangulated Ratings of Student Concept Generation Skills

Survey Item	Combined Mean
1. Rate your team's quantity of ideas generated for this project.	3.91 / 5.0
2. Rate your team's creativity of ideas generated for this project.	3.90 / 5.0
3. Rate your team's diversity (i.e. unique designs) of ideas generated for this project.	3.93 / 5.0

Open-ended responses were collected for each question in Table 5 asking respondents to elaborate on their ratings. The following responses are direct quotes from the respondents. Strengths related to concept generation by teams, as well as areas for improvement for concept generation, were identified by Faculty Directors, Industry Clients, and students.

One Faculty Director commented:

> *"It would be difficult to improve their final product. They had an incredible array of ideas and were able to implement most of them."*

Suggestions for improvement in concept generation performance from open-ended comments focused on generating an even wider range of ideas. One Faculty Director commented:

> *"They seemed a little hesitant to throw out ideas or they would rally behind a single idea versus a brainstorm. They seemed like they wanted an answer versus a list of options."*

One Industry Client wished the team would have:

> *"Come up with at least 5 ideas that the company mentor and customer had not thought of."*

Student comments included:

> *"Design Heuristics was a really interesting facet of the project. This was really fun and if it could be expanded that would be helpful, however, with limited time it seemed to be balanced well."*

Similarly, one student team member suggested the team should have:

> *"Thought outside of the box more, considered wilder ideas prior to latching on to a design path."*

Further tips for thinking outside the box included more research, less defensiveness around personal preferences for ideas, and more opportunities for using Design Heuristics. One student suggested:

> *"Having only one deck meant we all couldn't use them easily for brainstorming."*

A final analysis looked at factors driving design choices; student respondents could choose from the survey whether decisions were driven by time, the Faculty Director, or the Industry Client.

Table 6: Student Ratings of Influential Factors in Design Selection

Survey Item: What guided your team when making your final design selection? Check all that apply:	**Respondent Percentage**
1. Time	76%
2. Faculty Director	75%
3. Industry Client	74%

Results can be viewed in Table 6 and indicate similar influences from all factors in choosing designs. Comments from students endorsed all factors as equally influential. One student responded:

> "*Time: we needed to freeze the design in order to finish on time*"

While another student participant thought:

> *"The faculty adviser was the leading figure because he expected everything to get done. He didn't play a major role in what the design was, but he was the biggest push in getting everything done well."*

Others students suggested the client:

> *"Our company mentor was most influential in our selection because they were our customer so we had to build towards what they wanted."*

Still others added in money as the important factor:

> *"I checked time, but in reality it was money…"*

This comment suggests that leading factors vary by project.

Implications for Implementation in Industry Sponsored Capstone Design

It appears from the results that students experienced Design Heuristics as a useful training for accelerating the development of the project. It was reported as a novel approach that provided a unique perspective on their budding designs. This implies the utility of the 77 Design Heuristic cards for future iterations of capstone design courses. Students did not think additional in-class training would be necessary for the second semester in year-long projects. However, in post-survey results, some students did express the desire to learn additional or advanced techniques for applying the 77 Design Heuristics cards for projects that require additional concept generation during design iteration. This implies the need for some targeted team interventions at the beginning of the second semester in which individual teams might be selected for more work with the cards.

Student attitudes towards idea generation were positive at the post-assessment, with students expressing an interest in, and appreciation for, the importance of idea generation and the need to bring multiple designs to the client to involve them in the process. Students were able to generate a variety of strategies for concept generation, and results demonstrated the integration of Design Heuristics as a useful strategy on the post-assessment. Additional outcomes included satisfaction by advisors and students with idea generation for the project. These are all favorable outcomes for the senior design course and projects, and imply the need to continue existing Design Heuristics curriculum as well.

A take away from the data, and an area for improvement, is that students are primarily using the Design Heuristic cards early in the design process: they find that the greatest utility for the cards

is to launch their projects. Students seemed to view concept generation as a stand-alone phase that only happens early in design. This conception likely influenced their decisions to use, or not use, Design Heuristics later in the semester: students seemed to struggle to recognize the iterative nature of concept generation and development. We do not have the data to substantiate the root cause for these beliefs, but hypothesize that it may be due to their novice approach to product design. One way to support the continuous integration of the 77 Design Heuristics cards throughout the project is to train the Project Directors to have working sessions with their teams. These mid-design stage concept generation sessions would assist students with the transition and implementation of using the cards during the iteration design phase. Elective workshops for Project Directors, which target a more in-depth use of the cards, could be used to facilitate Project Director training.

It was found that drivers of the design process varied by team with faculty, clients, time, and money all driving the process depending on the individual circumstances inherent in every design project. This finding suggests that Design Heuristics might play a different role in the development of individual team projects and suggests some deeper investigation of project/heuristics interactions. Investigation of how individual teams are using the cards during second semester design is warranted to better understand how to train students to use the 77 Design Heuristics cards at different stages of the design process.

Conclusions and Future Work

The results of this work indicate that targeted training was beneficial and well received by students who were completing industry sponsored capstone design projects. It provided students with an additional technique for generating ideas to solve the complex projects that were proposed by their Industry Client. When left to their own devices to utilize the 77 Design Heuristic cards, students *chose* to use the cards early in the design process—not understanding or valuing that they could use the 77 Design Heuristic cards as prompts for concept generation during design iteration at the midpoint of the design process. This misconception could potentially cripple the progress of finding an innovative solution for their client, and we perceive this as a deficiency in training and coaching.

To improve the execution of concept generation *throughout* the entire design process and increase the utilization 77 Design Heuristic cards, there is a need to better understand why students opt to use the the 77 Design Heuristic cards early in the design process. Do the students perceive that the constraints of a sponsored project (e.g., time, money, client demands, etc.) as a barrier to concept generation? Do the Faculty Director or Industry Client move teams away from pursuing creative solutions and focus on safe designs that will ensure project success? Understanding the influence of these factors through future work will not only increase quality, quantity and diversity of the concepts generated, but also set the stage for the use of the 77 Design Heuristic cards in an industry setting.

We should note that, by the end of the project, students did identify using the 77 Design Heuristic cards as one of the three strategies they selected when generating ideas for their project. This strategy did not show up as a theme at the pre-assessment. It is possible that more students than identified through coding were using the cards, since there is evidence that students interchangeably used the words *brainstorming*, *concept generation* and *Design Heuristics*.

Ultimately, this study sets the groundwork for an approach to formally integrating concept generation into capstone design courses. We have built upon the previous work done by the inventors of the 77 Design Heuristic cards, with the engineering education practitioner in mind. Future studies will investigate strategies for integrating the cards deeper into the iterative process of project-based design.

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