Designettes in Capstone: Impact of Early Design Experiences in Capstone Education with Emphasis on Depth of Design Process Content

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Abstract

The engineering design process can be a complex and lengthy process, and be considered a daunting experience for engineering students embarking on their first full-length project. "Designettes" are a pedagogical approach to introducing parts of engineering design in such a way that students can experience it in a manageable, introductory fashion. In many design courses, students may experience design activities such as "Customer Needs Analysis," "Functional Decomposition," "Concept Generation," "Concept Selection" and "Prototype Planning" for the first time. One approach to increasing design experience to aid understanding of these activities is to use the designette exercise to provide the students with a framework of the design process. They can then rely this framework for their longer capstone projects. The designette is highly tailorable and an understanding of the appropriate factors related to its successful implementation is desired. We have used several versions of the designette approach over the past five years in our two-semester capstone design course. Each year we've implemented the designette across numerous projects, where teams of 3-8 students are also assigned year-long, externally sponsored projects. Previous research reported on the effects of varying the length of the designette and with the use of related and unrelated designettes to the students' year-long projects. In each use of the designette, the suite of five design activities mentioned above was presented in varying levels of depth of coverage. For the past two years, data has been gathered on the effect of varying the amount of design content provided on the effectiveness of the designette approach. Design content detail in the current year of designettes was increased by approximately 50% over previous years. Faculty and student feedback was primarily used to characterize and compare the designette's effectiveness. Initial results suggest a continued benefit of the inclusion of the designette approach to capstone design courses, with varying results from the depth of design process coverage.

1. Introduction

The use of the capstone design experience is common in Accreditation Board for Engineering and Technology (ABET) accredited engineering programs [1]. While there are several models for the capstone experience, each tailored to the institutional and program goals of a specific program, most are project-based and introduce, or reinforce the engineering design process and activities [2, 3, 4]. Often times, the capstone engineering design course is the first full application of the engineering design process and it can be a difficult endeavor to understand the full cycle and the impacts of each design choices when the project may last for a full year. This lack of understanding of the full process can be mitigated through the application of early, scoped exercises that provide scaffolding for the student for the remainder of the year. Such exercises have been implemented and documented as "designettes" [5] and serve as the foundation to the research of this paper. For several years, designettes have been explored at this institution in order to enhance our capstone design course and to find the optimal implementation of the experience. This paper presents the results of our latest research effort where we looked at the level of design content that should be present in the designette experience.

2. Related Research

The following sections explore related research on designettes (Section 2.1) and their specific application to capstone engineering courses (Section 2.2).

2.1. Previous Work in Designettes

Designettes can be understood as a type of active learning and collaborative project based learning (CPBL). There are many cases where the active learning and CPBL contain aspects of design. For example, reverse engineering can be used to teach students to understand functionality and how customer needs analysis drives product development [6, 7]. Exploration of everyday products has been used by Beaudoin and Llis [8] as a way to understand aspects of engineering design. Hands-on experiences can be tailored to provide design based "exploration of alternatives" [9]. Chesler [10] uses a computer simulation environment to facilitate exploration of alternatives specifically for client interaction in a redesign situation. More direct examples include design thinking courses and workshops developed and delivered at numerous institutions including Stanford, Harvey Mudd, University of Texas and the Air Force Academy [11, 12, 5, 13].

Although active learning, CPBL and improvements in capstone design content and delivery have been explored for decades, the concept of specifically focusing on, and intentionally designing, compressed design experiences has seen increased attention recently. A "designette." [11, 14, 15, 5, 16, 17, 18] as originally coined at the Singapore University of Technology and Design (SUTD), is described by the originators as glimpses, snapshots, small-scale, short turnaround and well-scoped design problems that provide a significant design experience."[5] The designettes can have many purposes including training in design process, opportunities to integrate engineering analysis into real-world problems and experience in multidisciplinary teamwork. Wood et. al. [5] provide 10 characteristics of a designette as shown in **Table 1** below.

Table 1. Basic Characteristics of a Small Scale Design Project (Designette)

1. Clearly stated learning objectives and learning outcomes within a subject area (science, engineering science, mathematics, humanities, arts, social sciences), within a design process, or within a skill set
2. Intrinsically motivating, interesting, and fun activity
3. Open-ended activity with no single "correct" answer
4. Innovation focus
5. Need-based, well scoped, empowering, and motivating problem
6. Opportunities to ideate, explore design variables, explore the aesthetic, theme, explore economic or policy issues, explore ergonomic features, or some combination
7. Prototyping of ideas, at least virtually as part of a simulation, or physically as a concept or functional model
8. Relatively low-cost materials for creating prototypes

9. Implementing technology, such as layer-based manufacturing/rapid prototyping equipment, for quickly transforming ideas into reality, and
10. Forums to experiment with, test, or compete with generated designs

These ten characteristics can be incorporated into a process that is used to develop designettes as shown in **Figure 1**. Use of the process has been shown to enhance the development of the designette both in terms of efficiency (how long the development takes) and effectiveness [14].

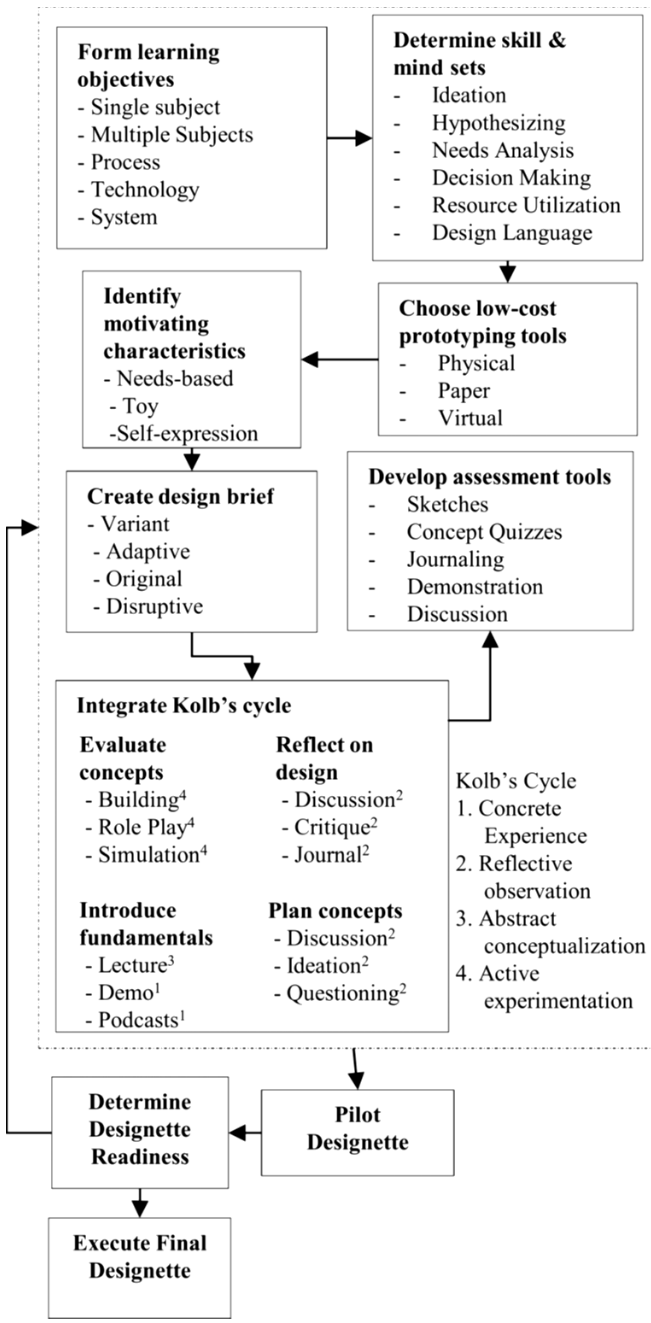

Figure 1. Process for designing designettes

2.2. Designette Use in Capstone Courses

Active learning and more specifically collaborative project based learning (CPBL) have been shown in multiple studies to enhance the learning process. Prince [19] provides an excellent review of much of this work. In addition to the impact on learning, design, open ended problem solving and systems thinking have been shown to encompass a critical set of skills according to industry experts [20, 21]. Designettes can be thought of as a type of CPBL with the characteristic that they include design content and design activities. While the pedagogical use of condensed design experiences is certainly not new, the term designette, and the focused research into the effect of these experiences, has seen renewed interest in recent years [14, 15, 5, 16, 22, 17, 11]. Based on constructivist learning theories that inform us that learning is enhanced when new experiences can build on the scaffold of previous experiences [23], designettes are being increasingly used to enhance young designers' ability to effectively implement structured design processes. One particular example of this is the use of designettes as part of a capstone course.

Capstone courses create wonderful opportunities for engineering students to apply the tools they have learned throughout their academic engineering training. In some cases a capstone experience may be the first time that students are applying the design process to a real industry, government, or societal problem. In other cases the students may have had some previous exposure to the design process. To the extent that students are not intimately familiar with a structured design process, implementation of the process in the real-world capstone project can be intimidating, problematic or even ill-advised. Constructivist learning theory [23] indicates that it may be more efficient and effective if students have some exposure to (or in the best case multiple iterations of experience with) the design process before they implement that process in the context of a real-world capstone project.

Capstone design courses provide a culminating engineering experience through design of a real-world product or system [24, 25, 17]. The design and creation of a functioning, engineered system in the context of a multidisciplinary team provides tremendous challenges as well as wonderful opportunities for the students. Incorporation of a designette prior to initiation of the actual capstone project can increase familiarity with the design process so that when they engage the actual capstone project, they can focus on the project itself, as opposed to spending significant effort struggling with implementation of the design process.

Teaching both design process and the actual capstone course(s) can occur in many forms [20]. Some universities have an initial course in design methods [1, 26, 11, 27], followed by either a one or two semester capstone course. Integration of the instruction in design methods or processes could also occur in the one or two semester capstone experience [28]. Although many curriculums have some small design content inserted into their early major's courses, the capstone experience may be the first time that students have been exposed to a formal, complete design process.

If the capstone project is the students' first experience with implementation of the formal design process, students are likely to have difficulty understanding the motivation behind the design process [17]. Techniques like "Customer Needs Analysis," "Functional Decomposition" and "Quality Function Deployment" are often met with resistance by students who want to proceed directly to a build/test phase. Even when students are encouraged to follow a formal, structured design process [7, 29, 30], they often fail to see the relationship between the different parts of the process as well as how the process increases efficiency from a time perspective and also increases their likelihood of development of a successful product or system. Even in industrial design environments, engineers sometimes fail to see the utility of following a formal design process [31].

In addition, research shows that it is beneficial to balance inductive learning and deductive instruction methods [32]. Mixing of inductive and deductive approaches has been shown both to enhance learning and to increase retention in STEM disciplines [33]. Most traditional instructional methods employ a deductive approach which involves introducing the general case for a concept or theory and then providing examples that support that generalization. However, students can benefit from an inductive technique as they tend to form a framework of understanding based on specific experiences or examples and then adopt a general concept. This is inductive learning. As a largely experiential course, the capstone can support the inductive learning style well. The necessary deductive-style teaching of accepted engineering design steps could be balanced with the inductive learning method by introduction of a designette prior to the team's engagement with the actual capstone project [17].

Additionally, context for designettes can be found by looking at the Kolb cycle (**Figure 2**). The Kolb model is characterized by a cycle that begins with concrete experience, proceeds with reflective observation and conceptualization, and ends, before restarting, with active experimentation [34]. Educational environments that incorporate all four steps in the cycle have been shown to more fully span the spectrum of student learning styles [32, 35, 36, 12]. Design projects most often can incorporate all four of the phases in the cycle: Concrete Experience, Abstract Hypothesis & Conceptualization and Active Experimentation. However, if the capstone experience is one of the first times that formal design process is introduced to the students, the opportunity for Reflective Observation becomes more difficult as the students are literally thrown into a high intensity design process where failure to develop a good product or system could lead to failure to obtain their engineering degree [17, 11, 18].

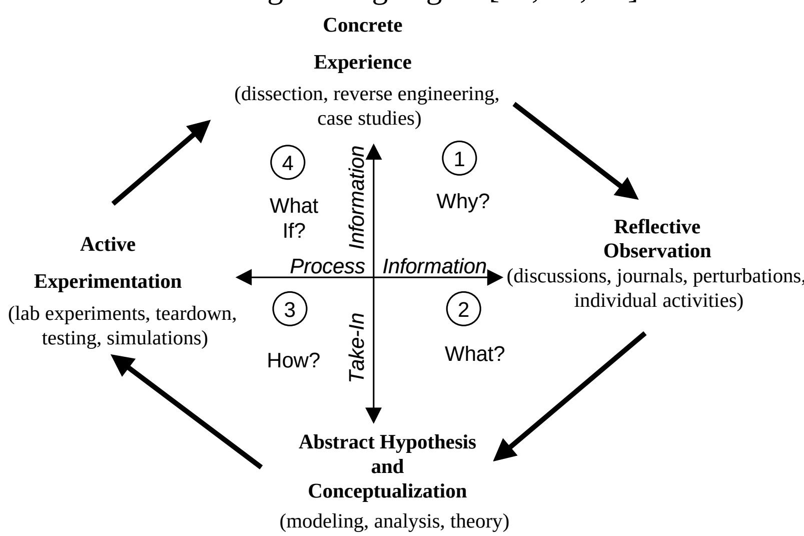

Figure 2. Kolb's cycle of learning

Use of a designette before the team engages with the actual capstone project can provide a context for students to become familiar with the design process in a less risk adverse situation than the actual capstone project affords. The familiarity with the design process which is gained from the designette can also increase confidence in the utility of the design process tools.

As a final framework for designette use in a capstone course, consider Blooms' Revised Taxonomy [37, 38, 39, 40]. The taxonomy provides a way to think about levels of learning as they progress through six levels toward more complex cognitive processes. The levels progress from remembering information, to understanding concepts, to applying concepts in familiar situations, to analyzing information, to evaluating hypotheses, and finish with creating new ideas (**Figure 3**). Capstone, or any design activity must progress to the highest level of the taxonomy, CREATING, to be successful. According to [41] higher levels in the taxonomy occur in cyclic patterns with lower levels. Also, access to the higher levels necessitates the understanding of fundamental concepts learned through use of the lower and mid-levels of the taxonomy [42]. Designettes provide the ability for students to experience the cyclic patterns and to engage with the fundamentals of design methods prior to the actual capstone project. This allows for more immediate access to the higher levels and especially to the CREATE level.

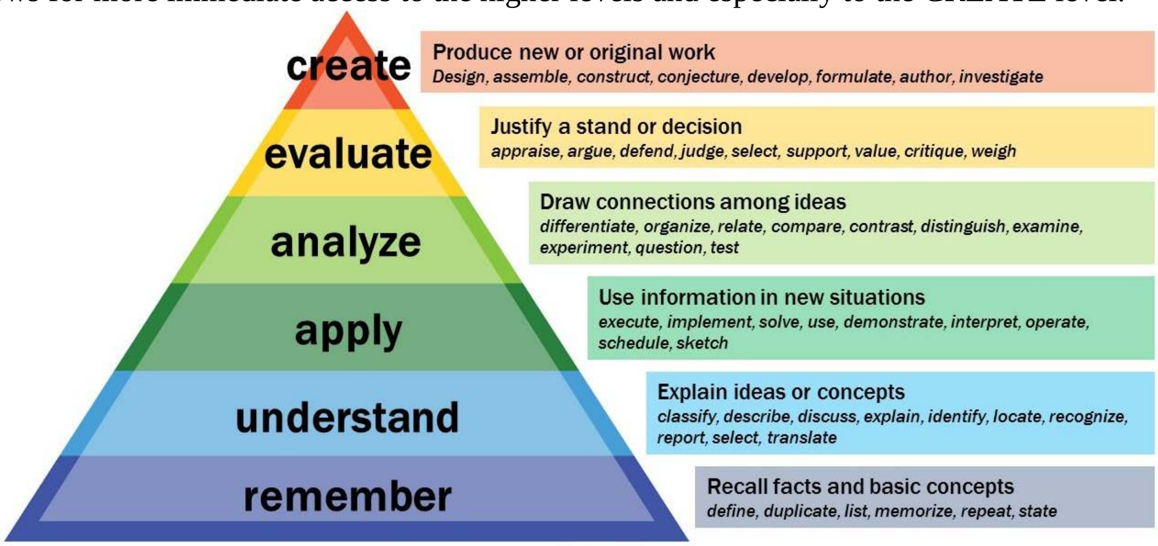

Figure 3. Bloom's revised taxonomy [40]

3. Research Approach

In previous works, we have detailed the application of various versions of a designette to our two-semester capstone education model. These variations between designette studies include the length of time and/or number of lessons set aside for the designette [11], as well as the content. For example, in one iteration, the designette's project content (a well-scoped design problem that was unrelated to the students' capstone, long-term, real-world project) was defined by the faculty and assigned to all of the student design teams (typically 8-10 distinct teams), while in a follow-on experiment, the project topic was varied by team, and the results were compared [17]. There has also been a growing interest in the optimal approach to increasing knowledge of and leveraging prototyping strategies [43, 44, 45, 46, 47, 48]. Several overlapping efforts in prototyping research exist; however, the authors chose to limit the variables to the current research by only directly exploring the depth of design content that is provided during the designette. Additionally, the level of design content provided is a key capstone characteristic of interest to larger efforts to understand the nature of successful capstone design. When capstones themselves, not to mention the designettes that support them, can be varied across at least 19 implementation spectrums it is important to gather additional information on the most effective design of engineering projects [49, 50].

In this current iteration, five of the design teams had unrelated design projects, while the remaining four teams performed projects that were a subset of their larger research project. This choice was at the discretion of each team's project advisor. The teams are formed from 37 senior-level engineering students. Most teams have a majority of mechanical engineering students with a minority of systems engineering or electrical engineering students. In this work, we sought to discover if varying the depth of instruction in the design process steps would have an effect on the students' execution of the designette project, as well as their execution of their longer-term, real world project. It is with this in mind that we developed our research question:

Research Question: What are the observable effects of varying the depth of design content provided to the students on the effectiveness of the designette approach?

Nine capstone design teams all received the same depth of coverage of the engineering design process in a group lecture setting over three lessons. In addition, the teams varied as to whether or not they performed projects that were "related" designette projects, or "unrelated". This was not a variable under deliberate study in this research. While a full design process will include numerous steps, our implementation of the designette included a subset of commonly accepted design methods. The methods we included in the designette are: Customer Needs Analysis, Functional Decomposition, Ideation, Concept Selection and Prototyping [7]. For all teams the designette experience spanned the first three class lesson periods, with a fourth lesson used for final presentations of the designette. The lessons were as follows:

- Lesson 1 – Content provided on Customer Needs data collection/analysis, designette introduced
- Lesson 2 – Content provided on Functional Decomposition, Design Ideation (Customer Needs results due)
- Lesson 3 – Decision Analysis and Prototyping (Functional Decomposition & Ideation due)
- Lesson 4 – Designette Final Presentations (prototypes & design analysis due)

The course uses a two-hour class period, so there was time for the faculty to present lesson content in the first hour with time remaining for the students to work in teams on their project during the remainder of class time. In previous years, three 30 minute lectures (90 minutes total) covered design activity content in a lecture format. The remaining ~80 minutes per lesson (~240 minutes total) was available for the teams to work on their designette projects, in addition to any time spent outside of class. In the current iteration, the design content lecture time and depth was increased approximately 50%, such that each lesson's lecture content increased to 45 minutes each (135 minutes total). The remaining ~65 minutes of class time each lesson (~195 minutes total) was available for the teams to work on their projects (see **Figure 4**).

	1st contact hour	*2nd contact hour*	*Work hr outside of class*
Previous iterations	30 minutes lecture	~80 minutes advised team work time	60 minutes additional team work time
Current iteration	45 minutes lecture	~65 minutes advised team work time	60 minutes additional team work time

Figure 4. Comparison of lecture content and work time for each designette lesson

The depth of design content was increased through use of additional lecture content, examples, and in-class exercises. As an example, for the lesson including Design Ideation as a topic, more time was spent explaining several methods for ideation: Morphological Analysis [7], Design by Analogy [51,52,53, 54], Mind Maps [55, 56], Prototyping [43, 44, 45, 46, 51, 57], C-Sketch [12], and Principles of Historical Innovators [12, 58]. For each of these methods, an example was provided and in-class activities allowed students to practice Morphological Design, Mind Mapping, and Principles of Historical Innovators. In previous years (lower depth version of the designette), the shorter instruction time only allowed for cursory overview of the various methods and practice in only one method. It was then expected that specific team advisors could expand on any method during work time as needed. The current version deliberately covered all methods and practiced several as a large group before breaking into the smaller teams for work time.

All teams remained the same between the designette and their larger capstone project, in part to limit this as a factor in assessing the designette's effects, and to gain the benefit of having the teams be complete with their team forming dynamics by the end of the designette phase. Both types of teams were expected to produce a complete mock-up, or basic functionality prototype, at the conclusion of the designette to be presented with their design presentation.

The hypothesized advantage of providing greater depth of instruction in the design tools is that the students would come away from the designette experience with (a) a better understanding of the engineering design process, (b) more realistic understanding of what is expected for each design product during the year-long project, (c) more relevant expertise in using the design tools (based on having used them correctly), and (d) a better quality product. Potential disadvantages of the increased lecture time are (e) reduced team forming due to less project work time, (f) reduced motivation/enthusiasm for the designette, (g) reduced familiarity with the laboratory and prototyping techniques, and (h) more time spent outside of class, possibly impacting other courses.

Advantages and disadvantages of the increased depth of design content instruction were observed from two main data sources. First, all students and faculty advisors were invited to provide feedback on the designette immediately following its completion by way of a feedback form. The form included 26 subjective questions from which respondents could indicate agreement through a Likert seven position response scale. Section 4.1 lists the 23 questions relevant to this research and combined response data. The form also included five additional questions asking what should be emphasized more, how long the designette should be, what the best part was, areas that should be changed, and a request for other comments. Faculty qualitative observations formed the second main data source. These were collected and are reported in Section 4.2. Faculty advisor feedback form comments and direct observations of the authors will be presented.

4. Results

The following subsections present the quantitative and qualitative results from this year's iteration of designette research. Section 4.1 presents data and discussion based on the student and faculty feedback questionnaires as compared to the same data from previous iterations of the designette implementation. Section 4.2 presents a summary of faculty qualitative observations experienced in several years and variations of designette implementation.

4.1. Quantitative results

Data was collected immediately following the designette completion from faculty and students through use of feedback questionnaires identical to previous iterations. Responses of the students and faculty advisors were combined and a simple comparison of averages between the two iterations is show in **Table 2**. The questions and their resulting data is rank ordered by the highest positive difference in the iterations where positive delta values indicate that the iteration with the increased design content delivery (i.e. 2017 version) resulted in higher agreement to the Likert survey questions. A negative delta value indicates that the iteration with the previous/standard design content delivery amount (i.e. 2016 version) resulted in higher agreement to the Likert survey questions.

Several observations can be made from the data in **Table 2**. First, it is observed that the large majority of measured responses resulted in an increase in agreement with the questions. As all questions are written in a manner that aligns high positive values with a desired agreement response, this general observation is a positive one. This indicates that on the whole, the increase in design content has had a positive effect on the student and faculty perception of the designette experience. In addition to this general observation, the top differences can also be explored.

The top positive differences observed occurred for the following questions: "The problem statement was clear, and our team knew how to proceed in solving the problem" (1.0 delta), "Helped me to know the capabilities of the XXXX Lab" (0.8 delta), "I had sufficient time to prototype" (0.8 delta), "Helped me understand the 'Prototyping Strategy' step in the design process" (0.7 delta), "Motivated me through competition with the other teams" (0.6 delta), and "Our team was able to collect customer needs data relevant to the mini-design in a timely fashion" (0.6 delta).

These are interesting as a set, but it may be more useful to explore the data from the perspective of our original hypotheses. Recall that we expected that the increase in design content would provide (a) a better understanding of the engineering design process, (b) more realistic understanding of what is expected for each design product during the year-long project, (c) more relevant expertise in using the design tools (based on having used them correctly), and (d) a better quality product. Items (a) and (c) are supported by the data above in that the questions related to understanding the five design activities (Customer needs, Functional Decomposition, Ideation, Concept Selection and Prototyping) are mostly positive. Understanding of Functional Description as a design activity was unchanged. Items (b) and (d) are best observed through the eventual year-long project outcomes from the capstones as they complete.

Table 2. Feedback on the designette experience (Likert 1-7 scale).

Questions	2016		2017		Delta	
	Mean	StDev	Mean	StDev	Mean	StDev
The problem statement was clear, and our team knew how to proceed in solving the problem.	4.7	1.4	5.7	0.8	1.0	-0.6
Helped me to know the capabilities of the Mech Lab	3.6	1.5	4.4	1.5	0.8	0.0
I had sufficient time to prototype	3.8	1.4	4.6	1.4	0.8	0.0
Helped me understand the "Prototyping Strategy" step in the design process	5.1	1.4	5.8	0.8	0.7	-0.6
Motivated me through competition with the other teams	3.8	1.6	4.4	1.6	0.6	0.0
Our team was able to collect customer needs data relevant to the mini-design in a timely fashion.	5.2	1.5	5.8	1.0	0.6	-0.5
Our team had enough understanding of the design subject to make progress within the time constraints.	5.4	1.1	5.8	0.8	0.4	-0.3
Was relevant to me personally	4.8	1.7	5.1	1.3	0.3	-0.4
Helped me understand the "Customer Needs Analysis" step in the design process	5.4	1.3	5.7	0.9	0.3	-0.4
The Designette is a valuable component of the capstone design experience.	5.2	1.5	5.5	0.8	0.3	-0.7
The design subject led to concepts that were able to be prototyped within the Mech Lab in a timely fashion.	5.1	1.4	5.4	1.0	0.3	-0.4
The Designette improved my understanding of the capstone design process.	5.6	0.1	5.9	0.8	0.3	0.7
The Designette had the right depth of instruction for the design process/tools.	4.8	1.2	5.0	1.1	0.2	-0.1
Was interesting	5.4	1.5	5.6	1.1	0.2	-0.4
Helped me get to know my team	6.0	1.1	6.2	1.2	0.2	0.1
The Designette had the right breadth of design process/tools (recall we covered 5: Customer needs, Functional Decomposition, Ideation, Concept Selection and Prototyping).	5.4	1	5.6	0.9	0.2	-0.1
Helped me understand the "Concept Generation" step in the design process	5.4	1.1	5.6	0.9	0.2	-0.2
Increased my motivation and enthusiasm	4.7	1.4	4.8	1.0	0.1	-0.4
The Designette did not go deep enough into the 5 design tools/steps.	3.4	1.5	3.5	1.5	0.1	0.0
Helped me understand the "Concept Selection (Pugh Analysis)" step in the design process	5.4	1.1	5.5	1.3	0.1	0.2
Helped me understand the "Functional Description" step in the design process	5.2	1.2	5.2	1.2	0.0	0.0
The Designette provided a design process framework that I can rely on in my full project.	5.4	1.2	5.3	1.1	-0.1	-0.1
Helped me to get to know my faculty advisor(s)	5.8	1.3	5.7	1.2	-0.1	-0.1
Helped me become familiar with my team's full project	3.1	1.8	2.6	1.4	-0.5	-0.4

There was one notable drop in overall agreement for this iteration—"Helped me become familiar with my team's full/sponsored project" (0.5 delta). This may be the result of a reduced amount of team work time that could be spent exploring year-long project knowledge outside of the designette project. Again, observations can be related back to the research hypotheses of that the increase in design content would result in disadvantages of (e) reduced team forming due to less project work time, (f) reduced motivation/enthusiasm for the designette, (g) reduced familiarity with the laboratory and prototyping techniques, and (h) more time spent outside of class, possibly impacting other courses. Disadvantage (e) and (g) do not appear to be realized. The data related to these areas indicate that the students' ability to get to know their team and the lab was still more positive than in the iteration with less design content. Disadvantage (f) may be a possible outcome due to the very low (but yet) positive delta value. Disadvantage (h) does not have observed data that we can base conclusions on at this time.

4.2. Qualitative results

Both faculty and students observed differences in the outcomes of the designette with the increased depth of design process instruction as compared to previous iterations with reduced instruction. These observations were provided by the respondents on their feedback forms.

In previous iterations in which there was reduced depth of instruction in the design process, faculty and students complained about insufficient understanding of the design process tools. These comments were mostly unseen after this iteration with more content provided, which is a positive, if expected, result. Numerous students commented that there was insufficient emphasis on prototyping in this iteration. This is a logical consequence of increasing the time spent on lecturing; however, the faculty decided it was a worthwhile tradeoff because the intent of the designette is to familiarize students with the design process, not primarily prototyping.

In previous (reduced-instruction) iterations of the designette, faculty members commented that the best parts of the designette are the opportunity for students to jump right in, "get their hands dirty", and be creative. This is a distinctly inductive teaching strategy. This highly experiential way of teaching the design steps is commonly understood to be a strength of the designette method. Fortunately, these comments were repeated in this iteration, despite the increased time devoted to lecture-based instruction. Therefore, it appears to continue to remain as the best part of the approach. Other faculty comments highlighted the students' opportunity to experience the complete design process, as has been noted in all previous offerings.

Faculty members offered several ideas on what should be changed on the designette. In previous offerings, several members indicated a desire to have more details and common guidance provided on the design steps. These comments were largely absent in this iteration, likely due to the increased instruction. In particular, faculty noted vastly improved execution of certain design tools, such as Customer Needs data collection, and Concept Selection, while students still struggled to properly implement the Function Description design tools. For Customer Needs, all teams collected survey data, but some performed focus groups and detailed Subject Matter Expert interviews that enhanced their results. For Concept Selection, some teams performed numerous iterations of decision matrices, which is common/expected for their real-world design projects. While prototyping time was reduced, the students made greater and more effective use of virtual prototypes, which was an unexpected benefit. As a result, the students gained expertise with numerous virtual prototyping tools and gained understanding of their relative value.

In summary, both faculty advisors and students view the designette approach positively. A common remark on the designette experience is the display of enthusiasm by the students and the benefit of team forming that occurs during this fast-paced experience. Lastly, another suggestion that might be considered by potential designette administering programs is to have the design teams present their results in a poster session format, rather than oral presentations.

5. Limitations

There are several limitations to the current research: self-reported data, small population, single institution, and bias of those reporting. As with any study that uses primarily self-reported data, there is a concern over its reliability in the respondents' understanding of what is being asked of them and is that understanding consistent across populations. The authors believe that reasonable care was take to alleviate both of these concerns with self-reported data, but also seek additional methods to objectively measure the effectiveness of the designette experience while also balancing the primary goal of top quality education for all capstone students each year. A limitation of this study also exists in the lack of final/objective learning outcome comparison for the projects. Final grades and success of the overall projects currently have too many uncontrolled variables to compare with at this time.

The second limitation could be that there was a small population size studied. In each year, there are roughly 50-70 students in the capstone under observation. Response rates for the participants are usually very good, but it is still a relatively small capstone enterprise as compared to major US engineering colleges. Additional colleges may be brought into future research as available to broaden the base of data for designette research. Similarly, this research was conducted only within a single institution, therefore the controlled variables which enable our conclusions, may need to be varied for applicability to other institutions.

Finally, there is a possibility of bias in those reporting. It was made clear to all respondents that the feedback would have no bearing on their overall designette or capstone grade; however, there can always exist the possibility that students desire to indicate a high agreement to questions that may reflect on their personal understanding of course topics. The maturity level of our students for this course, and additional explanation of the goals of this research should have served to minimize this limitation risk, but it is offered for consideration nonetheless.

6. Conclusions

Following several years of research in the use and optimization of the designette experience, a most recent iteration explored varying the depth of design content provided. The designette iteration this year added 50% more design content instruction during a four-lesson experience. Results were collected from faculty and student feedback questionnaires to compare this iteration to prior iterations. From this comparison, observations have been made. First, the overall responses indicated a general positive response to the increase design content instruction. Second, several hypothesized results were supported: students gained “a better understanding of the engineering design process," and "more relevant expertise in using the design tools (based on having used them correctly)." Also of interest is that hypotheses of certain possible disadvantages were not realized: students did not show "reduced team forming due to less project work time," nor "reduced familiarity with the laboratory and prototyping techniques." Other hypotheses were inconclusive at this time. In summary, the designette continues to be a valuable approach to supporting the learning styles and cycles most relevant to engineering education at the capstone level. In the future, we plan to work toward development of assessment techniques that will provide statistically significant correlations between various aspects of the designettes and the learning outcomes from the capstone course. With continued research into optimal implementation methods, it will continue to enhance our ability to produce well-educated engineers for the future.

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Bibliography

1. Engineering Accreditation Commission, "Criteria for Accrediting Engineering Programs, 2014 – 2015," Accessed 30 Jan 2015, Available: http://www.abet.org/.
2. Marin, J. A., J. E. Armstrong, and J. L. Kays. (1999). "Elements of an optimal capstone design experience." *Journal of Engineering Education* 88, no. 1; p. 19-22.
3. Zable, J., "Guest Editorial: 2007 National Capstone Design Conference," *Advances in Engineering Education*, vol. 2, no. 1, pp. 1-4, 2010.
4. McKenzie, L. J., M. S. Trevisan, D. C. Davis and S. W. Beyerlein, "Capstone design courses and assessment: a national study," in *Proceedings of the 2004 American Society of Engineering Education Annual Conference and Exposition*, Salt Lake City, UT, 2004.
5. Telenko, C., Wood, K.L., Frey, D., Dritsas, S., Kaijima, S., Tan, U., Moreno, D., Rajesh, M., Foong,S., and Pey, K.L. (2015). "Designettes: New Approaches to Multidisciplinary Engineering Design Education," *Journal of Mechanical Design (JMD)*, MD-15-1178.
6. Wood, K. L., Jensen, D., Bezdek, J., & Otto, K. N. (2001). "Reverse engineering and redesign: Courses to incrementally and systematically teach design." *Journal of Engineering Education*, 90(3), 363.
7. Otto, Kevin and Wood, Kristin. (2012). *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.
8. Beaudoin, D. L., and Llis, D. F. O., (1995), "A Product and Process Engineering Laboratory for Freshmen," *J. Eng. Educ.*, 84(3), pp. 279–284.
9. Linsey, J., Talley, A., Jensen, D., Wood, K., (2009-Winter) "From Tootsie Rolls to Broken Bones: An Innovative Approach for Active Learning in Mechanics of Materials," *Advances in Engineering Education Journal*, Vol. 1, Number 3.
10. Chesler, N. C., D'Angelo, C. M., Arastoopour, G., and Shaffer, D. W., (2011), "Use of Professional Practice Simulation in a First-Year Introduction Engineering Course," *Proceedings of the American Society of Engineering Education Annual Conference*, Vancouver, BC, pp. 22.15851–22.1585.9.
11. Cooper, C.A., M. Anderson, C. Bruce, S. Galyon Dorman, D. Jensen, K. Otto, K. Wood. (2015). "Designettes in Capstone: Initial Design Experiences to Enhance Students' Implementation of Design Methodology," *In Proceedings of the 122nd American Society for Engineering Education (ASEE) Annual Conference and Exposition*, Seattle, WA, June 14-17.

12. White, Christina, Wood, Kristin, Jensen, Daniel. (2012 Oct-Dec). "From Brainstorming to C-Sketch from Principles of Historical Innovators: Ideation Techniques to enhance Student Creativity," *Journal of STEM Education*, vol 13, no 5.
13. Kadlowec, J., Bhatia, K., Chandrupatla, T. R., Chen, J. C., Constans, E., Hartman, H., Marchese, A. J., von Lockette, P., and Zhang, H., (2007), "Design Integrated in the Mechanical Engineering Curriculum: Assessment of the Engineering Clinics," *ASME J. Mech. Des.*, 129(7), pp. 682–691.
14. Wood, K. L., Mohan, R. E., Kaijima, S., Dritsas, S., Frey, D. D., White, C. K., ... & Pey, K. L. (2012). "A Symphony of Designiettes: Exploring the Boundaries of Design Thinking in Engineering Education." In *Proceedings of the 119th Annual ASEE Annual Conference & Exposition*, Paper AC2012-4004, San Antonio, TX.
15. Telenko, C., B. Camburn, K. Hölttä-Otto, K. Wood, and K. Otto. (2014). "Designettes: New approaches to multidisciplinary engineering design education." *Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2014).* August 17-20, 2014, Buffalo, New York, USA.
16. Wahlquist, Joseph A., Jensen, Daniel D., Wood, Kristin L., Fitle, Kyle, and Carte, David. (2013 June). "Using Mini Design Competitions in Capstone," In *Proceedings of the 120th ASEE Annual Conference & Exposition*, Atlanta, GA.
17. Cooper, C., Anderson, M., Jensen, D., Wood. K., (June 2016), "Designettes in Capstone: Characterizing the Impact of Early Design Experiences on Students' Capstone Education",- *Proceedings of the American Society of Engineering Education Annual Conference*, New Orleans, LA.
18. Wood, K., Frey, D., Crawford, R., White, C., Mohan, R., Dym, C., Kaijima, S., Dritdsas, S., Jensen, D., (June 2012), "A Symphony of Designiettes – Exploring the Boundaries of Design Thinking in Engineering Education", *Proceedings of the American Society of Engineering Education Annual Conference*, San Antonio, TX.
19. Prince, M., (2004), "Does Active Learning Work? A Review of the Research," *J. Eng. Educ*., 93(3), pp. 223–231.
20. Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). "Engineering design thinking, teaching, and learning." *Journal of Engineering Education*, 94(1), 103-120.
21. McMasters, J., (2004), "Influencing Engineering Education: One (Aerospace) Industry Perspective," *Int. J. Eng. Educ.*, 20(3), pp. 353–371.
22. Otto, K., Camburn, B., Wood, K., Bouffanais, R., Kyoseva, E., Yee, L. H., ... & Mathur, A. (2014). Integrated 2D Design in the Curriculum: Effectiveness of Cross-Subject Engineering Challenges. *In Proceedings of the ASEE Annual Conference (Vol. 24).*
23. Steffe, Leslie P., and Jerry Edward Gale, eds. (1995). *Constructivism in education*. Hillsdale, NJ: Lawrence Erlbaum.
24. Dutson, A. J., Todd, R. H., Magleby, S. P., & Sorensen, C. D. (1997). "A Review of Literature on Teaching Engineering Design Through Project Oriented Capstone Courses." *Journal of Engineering Education*, 86(1), 17-28.
25. Dutson, A., Green, M., Wood, K., & Jensen, D. (2003, June). "Active learning approaches in engineering design courses." *In Proceedings of the 2003 ASEE Annual Conference and Exposition.*
26. Otto, K., Wood, K. L., Murphy, M. D., & Jensen, D. D. (1998, June). "Building better mousetrap builders: Courses to incrementally and systematically teach design." *In Proceedings of the ASEE Annual Conference and Exposition.*
27. Howe, S. (2010), "Where Are We Now? Statistics on Capstone Courses Nationwide," *Advances in Engineering Education*, vol 2, no. 1.
28. McKenzie, L. J., Trevisan, M. S., Davis, D. C., & Beyerlein, S. W. (2004, June). "Capstone design courses and assessment: A national study." *In Proceedings of the 2004 American Society of Engineering Education Annual Conference & Exposition* (pp. 1-14).
29. Ullman, D., *The Mechanical Design Process*, 5th ed., (2010), McGraw Hill.
30. Dym, C., Little, P., *Engineering Design, A Project-Based Introduction*, (2000), Wiley.
31. Green, M., Jensen, D., and Wood, K. (2009). "Design for Frontier Contexts: Classroom Assessment of a New Design Methodology with Humanitarian Applications," *International Journal of Engineering Education*, vol 25, no 5.
32. Felder, R. M., & Silverman, L. K. (1988). "Learning and teaching styles in engineering education." *Engineering Education*, 78(7), 674-681.

33. Kober, N., (2014), *Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering*, National Academies Press, Washington, DC.
34. Kolb D. (1984). *Experiential learning: experience as the source of learning and development.* Englewood Cliffs, New Jersey: Prentice Hall.
35. Jensen, D.D. and K.L. Wood (2000). "Incorporating Learning Styles to Enhance Mechanical Engineering Curricula by Restructuring Courses, Increasing Hands-on Activities, & Improving Team Dynamics." In *ASME Publication and Presentation for the Award for the Most Innovative Curriculum for the Year 2000, Presented at the ASME Annual Conference*. Orlando, FL
36. Jensen, D.D., M.D. Murphy, and K.L. Wood. (1998). "Evaluation and Refinement of a Restructured Introduction to Engineering Design Course Using Student Surveys and MBTI Data." *In Proceedings of the ASEE Annual Conference and Exposition*. Seattle, WA.
37. Bloom, B. S., (1984), *Taxonomy of Educational Objectives Book 1: Cognitive Domain*, Addison Wesley Publishing Company, White Plains, NY.
38. Anderson, L. W., Krathwohl, D. R., Airasian, P. W., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., Raths, J., and Wittrock, M. C., (2000), *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*, Abridged Edition/Pearson, New York.
39. Anderson, L., and Northwood, D., (2002), "Recruitment and Retention Programs to Increase Diversity in Engineering," *International Conference on Engineering Education*, Manchester, UK, pp. 1–5.
40. Armstrong, Patricia, "Bloom's Taxonomy," Vanderbilt University Center for Teaching, website: https://cft.vanderbilt.edu//cft/guides-sub-pages/blooms-taxonomy/ , Date accessed: 12 Feb 17.
41. National Research Council, (2000), *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*, The National Academies Press, Washington, DC.
42. Calabro, K., Kiger, K., Lawson, W., and Zhang, G., (2008), "New Directions in Freshman Engineering Design at the University of Maryland," *ASEE/IEEE Frontiers in Education Conference*, Saratoga Springs, NY, Oct. 22–25, pp. T2D:6–11.
43. Camburn, B., Dunlap, B., Gurjar, T., Hamon, C., Green, M., Jensen, D., ... & Wood, K. (2015). "A Systematic Method for Design Prototyping." *Journal of Mechanical Design*, 137(8), 081102.
44. Camburn, B., Dunlap, B., Linsey, J., Viswanathan, V., Jensen, D., Crawford, R., ... & Wood, K. L. (2013). "Using Design Problem Characteristics to Build a Prototyping Strategy." *In Proceedings of the ASEE Annual Conference.*
45. Camburn, B. A., Dunlap, B. U., Kuhr, R., Viswanathan, V. K., Linsey, J. S., Jensen, D. D., ... & Wood, K. L. (2013, August). "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment." *In Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V005T06A033-V005T06A033). American Society of Mechanical Engineers.
46. Camburn, B. A., Sng, K. H., Perez, K. B., Otto, K., Wood, K. L., Jensen, D., & Crawford, R. (2015, August). "The Way Makers Prototype: Principles of DIY Design." *In Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V007T06A004-V007T06A004). American Society of Mechanical Engineers.
47. Perez, K.B., Otto, K.N., and Wood, K.L., (July 2015) "Crowd-sourced Design Principles for Leveraging the Capabilities of Additive Manufacturing," *In proceedings of the International Conference on Engineering Design (ICED)*, Milan, IT, ICED15-396.
48. Jensen, D., Randell, C., Feland, J., & Bowe, M. (2002). A study of rapid prototyping for use in undergraduate design education. *In Proceedings of the 2002 ASEE Annual Conference*, pp. 7.113.1-7.113.15, Montreal, Canada, 16-19 June, 2002.
49. Cooper, C. A., J. M. Fulton and J. J. Homan, "A multi-spectrum framework for characterizing interdisciplinary capstone design experiences," in *Proceedings of the 13th Annual Conference on Systems Engineering Research (CSER)*, Stevens Institute, Hoboken, NJ, 2015.
50. Cooper, C.A., J. M. Fulton and J. J. Homan, "Initial Application of a multi-spectrum characterization framework for interdisciplinary capstone design experiences," in *Proceedings of the 14th Annual Conference on Systems Engineering Research (CSER)*, Huntsville, AL, 2016.
51. Marshall, S., Crawford, R., Jensen, D., "Analogy Seeded Mind-Maps: A Comparison of Verbal and Pictorial Representation of Analogies in the Concept Generation Process", ASME Intl. Design Engineering Technical Conference, Charlotte, NC, Aug, 2016.

52. Marshall, K., Crawford, R., Jensen, D., “Analogy Seeded Mind-Maps: A Simple and Quick Design-by-Analogy Method,” Proceedings of the American Society of Engineering Education Annual Conference, Seattle, WA, June 2015.
53. Murphy, J., Fu, K., Otto, K., Yang, M., Jensen, D., Wood, K., Function Based Design-By-Analogy: A Functional Vector Approach to Analogical Search, ASME Journal of Mechanical Design, #136-10, Oct, 2014.
54. Camburn, B., Jensen, D., Otto, K., Crawford, R., Wood, K., Designing Biologically Inspired Leaf Structures: Computational Geometric Transport Analysis Of Volume-To-Point Flow Channels, Engineering With Computers, 31:361-374, 2015.
55. Buzan, T., Buzan, T., The Mind Map Book: How to Use Radiant Thinking to Maximize Your Brain's Untapped Potential, Penguin Publishing, 1993.
56. Marshall, S., Crawford, R., Jensen, D., “Analogy Seeded Mind-Maps: A Comparison of Verbal and Pictorial Representation of Analogies in the Concept Generation Process”, ASME Intl. Design Engineering Technical Conference, Charlotte, NC, Aug, 2016. Camburn, B., Green, M., Dunlap, B., Jensen, D., Gurjar, T., Crawford, R., Hamon, C., Otto, K., Wood, K., “A Strategic Method for Design Prototyping,” *ASME Journal of Mechanical Design*, 137(8), Aug 01, 2015.
57. Camburn, B., Viswanathan, V., Linsey, J., Otto, K., Crawford, R., Jensen, D., Wood, K., “Design Prototyping Methods: State-of-the-art in Technology, Strategies and Heuristics,” *Design Science Journal*, Revised for Reviewers, April, 2016.
58. Larsson, Ulf, Editor, “Cultures of Creativity – The Centennial Exhibition of the Nobel Prize,” Science History Publications, 2001.