

Mapping between design activities and external representations for engineering student designers

Monica E. Cardella, Cynthia J. Atman and Robin S. Adams, Center for Engineering Learning and Teaching, University of Washington, Box 352183, Seattle, WA 98195-2180, USA

Many design researchers have attempted to characterize design through the different activities the designer exhibits, such as problem framing, solution generation, and evaluating alternative solutions. Others have documented the way that sketching supports design. This study combines these approaches to understanding design by exploring the interplay between designers' representations and their design activities in a set of four case studies. We analyzed verbal protocols collected from two senior and two freshman engineering students. The four students exemplify the significant design activity findings from a previous study. In this paper, we present the results from the analysis of the four design protocols, focusing on the relationship between representation and design activity, and on differences between the freshmen and seniors in our sample in the way that they make and use design sketches. We discuss these findings with a focus on improving design education.

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An industrial engineer in San Francisco manages a supply chain. A civil engineer in New York sketches a new bridge. A mechanical engineer in Braunschweig envisions an aerodynamic automobile body. Each is practicing engineering; each designs. For today's students to become these proficient engineers, they too must master design skills. Therefore, teaching engineering design is a goal that each engineering curriculum needs to address. To succeed in teaching design, engineering faculty must understand not only design but also how students learn design. Research in education suggests that understanding students' initial conceptions of design—how they approach design before receiving instruction—supports the development of student instruction on design processes (Newstetter and

Corresponding author:
Cynthia J. Atman
atman@engr.washington.edu



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McCracken, 2001). Research also shows that sketching supports design (Ullman et al., 1990; Verstijnen et al., 1999; McGown et al., 1998; Kavakli et al., 1998; Cross, 2001), so understanding students' natural tendencies related to their use of sketching as they design is an important starting point for enhancing design instruction.

This study explores four case studies of how engineering students sketch and use their sketches as they solve design problems. In addition to exploring students' use of sketches, we examine an array of representational activities that complement and support students' design activity. We use the term 'representational activities' to mean activities using external representations of information—problem statements, diagrams, written responses created by the students and equations in addition to sketches. Our research question is: do engineering students' use of external representations differ according to type of design activity or stage in the design process? Before presenting the methodology and results of the study undertaken, we first present a review of research that serves as our theoretical foundation. This includes methods for analyzing design activity, some key findings in terms of expertise in design and novice design behaviors, and findings specific to the use of sketching in design.

1 Theoretical framework

Design expertise can be characterized by a variety of methods, findings, and analysing the way that design expertise is acquired (Turns et al., 2002). One of the most prevalent approaches to studying design is Verbal Protocol Analysis (VPA), a rigorous, empirical method for studying cognitive processes (Ericsson and Simon, 1993). VPA is a well-documented approach to understanding what a designer is thinking while solving a problem; it has both been applied to practicing engineers (Cross et al., 1996) and has been shown to be a reliable method of studying engineering students' design cognition (Atman and Bursic, 1998). Research in engineering design has also been conducted via questionnaires (Römer et al., 2001), ethnographic studies (Bucciarelli, 1994), observation (Visser, 1990), experimental study (Thomas and Carrol, 1979), and the use of electroencephalograph (EEG) records (Göker, 1997). Akin and Lin (1995) suggest that visual—graphic data should be a method of analyzing design, since drawings play a key role in design and verbal data (collected from VPA) cannot explain the design process alone.

From the application of these methodologies, a great body of research in engineering design has accumulated. Cross (1999) summarizes design by

describing it as rhetorical, exploratory, emergent, opportunistic, abductive, reflective, ambiguous and risky. Visser (1990) and Ball and Ormerod (1995) have explored the role of opportunism in design, Thomas and Carrol (1979) discovered that designers approach problems as if they were ill-defined (even when they are not), Dorst and Cross (2001) reported on the co-evolution of solution and problem spaces and discovered that designer's 'creative leap' bridges these two spaces by articulation of a concept. Fricke (1996) identified the operation of a 'balanced search' for solution alternatives as a strategy employed by successful designers and Cross and Clayburn Cross (1998) have identified the importance of problem framing—the use of a guiding principle—as a design strategy.

Many researchers have also made contributions to specifically understand *students'* design tendencies. Adams (2001) found that both the time spent iterating and the types of iterations students made correlated with the quality of their designs. Christiaans and Dorst (1992) found that some students are unable to progress past information gathering into solution generation; in their study, Atman et al. (1999) found that a large proportion of the students exhibiting this type of behavior produced inferior solutions. Atman and Bursic (1996) also found that even minor interventions (e.g. reading a textbook) can positively impact student design behavior. Likewise, Radcliffe and Lee (1989) found that the intervention of instructing students to follow a systematic approach can help students design in an effective manner. Römer et al. (2000) have shown that sketching, one type of an external representation, supports students' design, particularly in the early stage of problem formulation.

Researchers have taken a number of approaches to understanding designers' use of representations. Ullman et al. (1988) considered the different levels of abstraction of sketches, and Kavakli et al. (1998) have shown that designers sketch objects part by part rather than as a whole. Many researchers believe that sketching provides an external memory to aid the designer (Ullman et al., 1988) while others suggest that sketching primarily compensates for limitations in imagery (Verstijnen et al., 1998). Verstijnen et al. also suggest that sketches are more often used when designers are performing tasks where they are restructuring images rather than combining parts to make a new image. This coincides with Purcell and Gero's (1998) suggestion that sketches allow designers to notice new, emergent elements of a design that the designer is unable to perceive via an internal representation. This allows designers an opportunity to shift their focus and consider other elements of the design. Thus, sketching supports the iterative facet of design. Cross

(1999) also suggests that sketching acts as an ‘intelligence amplifier,’ allowing the designer to simultaneously consider multiple aspects of the design by what Goldschmidt (1992) calls interactive imagery, the ‘reading’ of information from a sketch or series of sketches while simultaneously generating them. In addition to supporting the specific design activities of iteration and problem formulation, external representation supports the communication of design decisions (Römer et al., 2001).

The study presented in this paper further investigates how sketching, in addition to other representational activities, supports individual activities in engineering students’ design processes. Specifically, we have used a series of four case studies to explore the types of representational activities that students exhibit while engaged in design activities such as problem definition, idea generation and evaluation. This study provides insight into a question prompted by Akin and Lin (1995): to what degree do visual—graphical activity and verbal activity correlate? While Kavakli and Gero (2002) offer insight into this question by contrasting the behavior of an architecture student and a practicing architect, the study presented in this paper focuses solely on students and is concerned with engineering design rather than architectural design.

In this paper we present the research design, the coding scheme used to identify use of external representations, a discussion of each of the four cases and implications for engineering design education.

2 Methodology

The data for the current study is a subset from a freshmen—senior comparison dataset, which is composed of 24 senior and 26 freshman engineering students who ‘thought-aloud’ as they designed a playground for a fictitious neighborhood. The participants were initially given a problem statement and a diagram of the lot. Additionally, the participants were able to request more information from the administrator during the course of the experiment. The participants were audio and video taped as they solved the problem and their verbal protocols were transcribed, segmented and coded for design step (Atman et al., 1999) (see Table 1).

Eight of the ten design step codes were applied to the segmented transcripts. Because the problem statement was provided, it was not necessary for the participants to identify a need. The participants also did not implement their final designs. During the original analysis of this data, the eight design steps were grouped into three design

Table 1 Design activity coding scheme (Atman and Bursic, 1996)

Design activity	Description
<i>Problem Scoping</i>	
Identifying a need	Identify basic needs (purpose, reason for design)
Problem definition (PD)	Define what the problem really is, identify the constraints, identify criteria, reread problem statement or information sheets, question the problem statement
Gathering information (GATH)	Search for and collect information
<i>Developing Alternative Solutions</i>	
Generating ideas (GEN)	Develop possible ideas for a solution, brainstorm, list different alternatives
Modeling (MOD)	Describe how to build an idea, measurements, dimensions, calculations
Feasibility analysis (FEAS)	Determine workability, does it meet constraints, criteria, etc.
Evaluation (EVAL)	Compare alternatives, judge options, is one better, cheaper, more accurate
<i>Project Realization</i>	
Decision (DEC)	Select one idea or solution among alternatives
Communication (COM)	Communicate the design to others, write down a solution or instructions
Implementation	Produce or construct a physical device, product or system

stages: Problem Scoping (problem definition and gathering information), Developing Alternative Solutions (generating ideas, modeling, feasibility analysis and evaluation) and Project Realization (decision and communication). While we use the term ‘design step’ and ‘design stage’ to discuss these design activities, these design activities do not actually occur in a strictly linear fashion.

For the initial analysis of this data, total time spent on the problem and on each design activity step was recorded and the percent of time spent on each design activity was calculated. Additionally, the number of transitions between design steps and the frequency of these transitions was calculated for each participant. Experimenters evaluated participants’ final solutions for quality and also assessed the number of stated constraints (out of seven) met. The quality of solution score is based on three components: criteria given in the problem statement, additional criteria appropriate for the student’s particular design and ratings for diversity of activities, aesthetics, protection from injury, uniqueness and technical feasibility. The three components were weighted equally to obtain a score that could range from 0 to 1. For a subset of the scores, two evaluators independently scored the

data and then checked the consistency of their scores to confirm the reliability of the scoring process.

2.1 Participants

To investigate the engineering students' use of external representations, we selected four students (two seniors and two freshmen) from the original dataset. These four participants represent the main findings from an investigation of relationships between design process and design product (Atman et al., 1999). For the freshmen in the original study, quality of product is correlated with number of constraints met, total amount of time spent solving the problem, amount of time spent making evaluations, amount of time making decisions and percent of time spent in the developing alternative solutions stage. For the seniors, the only design process variable correlated with the overall quality of solution score is number of transitions between design steps. However, number of constraints met, another measure of solution quality, was correlated with the percent of time spent in the Problem Scoping (or problem formulation) stage and percent of time spent in the Developing Alternative Solutions stage. Additionally, seniors tend to spend more time in the later steps of the design process—particularly the project realization phase—than freshmen. Table 2 shows how each of the four case study students performed relative to the average performances for freshmen and seniors. Finally, one of the freshmen selected as a case study (F2) did not exhibit any sketching behavior. This participant offers insight as an alternative to a sketching-supported design process.

2.2 Coding scheme

As previously mentioned, this study examines the relationship between verbal activity and visual—graphic activity. To accomplish this, we

Table 2 Characteristics of study participants

	Seniors (mean)	S1	S2	Freshmen (mean)	F1	F2
Number of constraints met	4.9	4	5	5	5	3
Quality score	0.51	0.627	0.387	0.45	0.526	0.187
Total time (in min)	110.0	130.6	104.7	104.0	98.3	37.45
Percent of time in Problem Scoping (%)	18.1	17.1	7.9	18.4	14.9	26.3
Percent of time in Developing Alternative Solutions (%)	76.9	75.9	78.9	78.5	83.4	73.7
Amount of time in evaluation (s)	120	385	22	84	27	0
Amount of time in decision (s)	48	64	75	24	43	0

annotated the pre-existing transcripts with a new set of representation codes and compared the representational activity codes to the existing design activity codes. The representation coding scheme was designed to capture when and how students create and use visual information. While sketching was a main focus, we also documented students' use of written solutions, calculations and information that had been given to them.

The representation coding scheme developed for this analysis (see Table 3) shares characteristics of Akin and Lin's (1995) activity based model, Ullman et al.'s (1990) 'marks-on-paper', Goldschmidt's (1992) description of serial sketching, and Kavakli and Gero's (2002) analysis of concurrent cognitive actions.

The primary author and another researcher developed the coding scheme through an iterative process of applying the scheme to other protocols (other students solving design problems), and making

Table 3 Representation coding scheme

Representation activity	Definition
Read given text (Given)	Reading/looking at information that is provided by the experimenter
Look at given diagram (Diagram)	Looking at the diagram of the lot.
Write own text (Write)	Creating a written response or writing down ideas to be used later.
Read own text (Read)	Reading a response written by the participant.
Sketch own picture (Sketch)	
New picture (New Sketch)	Creating a new picture, label or arrow.
Continue picture (Continue Sketch)	Continuing to work on a sketch by drawing a picture, attaching a label or drawing an arrow.
Add to picture (Add to Sketch)	Returning to a sketch after engaging in a different activity or working on a different sketch.
Look at own picture (Look at Sketch)	Looking a sketch or equation, 'reading' information off it, or looking at an equation.
Calculate (Calculate)	Creating an equation or making a calculation.
Look off (Look Off)	Staring off into space and not fixing attention on any material.
Uncodable (No Code)	Leaning outside the range of the video camera or looking at an unidentifiable material (given information, written response or sketch).

amendments to the scheme. They then independently applied the final coding scheme to each of the four transcribed protocols by viewing the videotape and annotating the verbal protocol. Each segment was coded for every possible representation activity, meaning that each segment could be coded with several representational activities. Each coded segment was then evaluated for inter-rater reliability, yielding an average rating of 92% agreement.

2.3 Example sketches

[Appendix A](#) shows an example of the most common type of sketches created by the participants. The two sketches are created by one of the study's participants (case study Participant S1). The two sketches are two versions of the playground's layout. The participant created the first layout early in the design process. Participant S1 first used the layout to calculate the dimensions of the sandbox and to assign a cost to the sand (Modeling). After considering the sandbox, this student began to think of other pieces of equipment to add to the layout (Generating Alternatives). This, however, caused S1 to reconsider the problem's constraints (Problem Definition). As Participant S1 continued to design the playground, this participant continued to work on both the individual pieces of equipment and the layout of the playground as a whole. After finishing the iterative process of designing the playground layout and the individual pieces of equipment, Participant S1 created the second layout — the final playground design.

3 Results

To simplify the discussion of the results, we will report findings only for the broader categories of: Given, Diagram, Write, Sketch, Look at Sketch, Calculate and Look Off. [Figure 1](#) displays matrices for our first case study. The matrices for all four case studies are presented in [Figure 2](#). The matrices show the intersection of design activities and representation activities. The matrices present dense information so we present the results for the first case study in detail in [Figure 1](#) to provide an in-depth explanation of the data presented in [Figure 2](#).

3.1 Case study S1: high-scoring senior

Participant S1 exemplifies a typical senior in terms of number of the problem's constraints met, percent of time spent in the Problem Scoping stage and percent of time in the Developing Alternative Solutions stage (See [Table 2](#)). Participant S1 did, however, earn an above average quality score (0.63). This participant thoroughly covered each of the verbal design and representational activity interactions (see [Figure 1](#)).

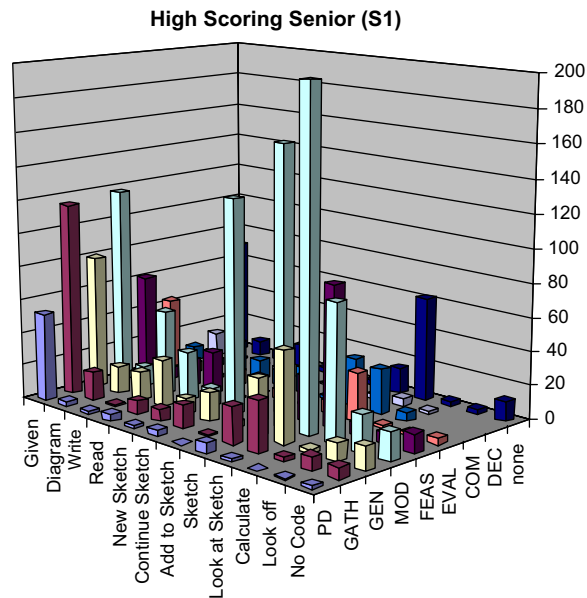


Figure 1 Three dimensional bar chart for S1

The three dimensional bar chart in Figure 1 shows participant S1's use of representations with respect to design step. Each bar in the chart represents the number of segments coded for a specific design activity in relation to a specific representational activity. For example, at the intersection of Diagram and GEN, we see that in 16 segments S1 was looking at the diagram while generating ideas. The bars at the intersections of Diagram and GEN and Diagram and GATH (17 segments) are the two largest bars for the Representational Activity 'Diagram.' This means that most of the time that S1 looked at the diagram, he was using it to either gather information or generate ideas. S1 looked at the diagram while performing each of the eight verbal design activities, but the main design activities associated with looking at the diagram for S1 are gathering information and generating ideas.

If we turn our focus to the design steps, we see that S1 communicated the design in approximately 100 segments. S1 sketched 29% of the time and looked at sketches 27% of the time that S1 communicated the design, so we see that these two bars are the two largest bars for the communication design step. From the bar chart we also see that Given and Look at Sketch are the two predominant representation activities for S1 and that sketching is associated with modeling and communication.

At this point we return to our main measures of interest for S1. For the seniors, these measures were percent of time in the Problem Scoping stage,

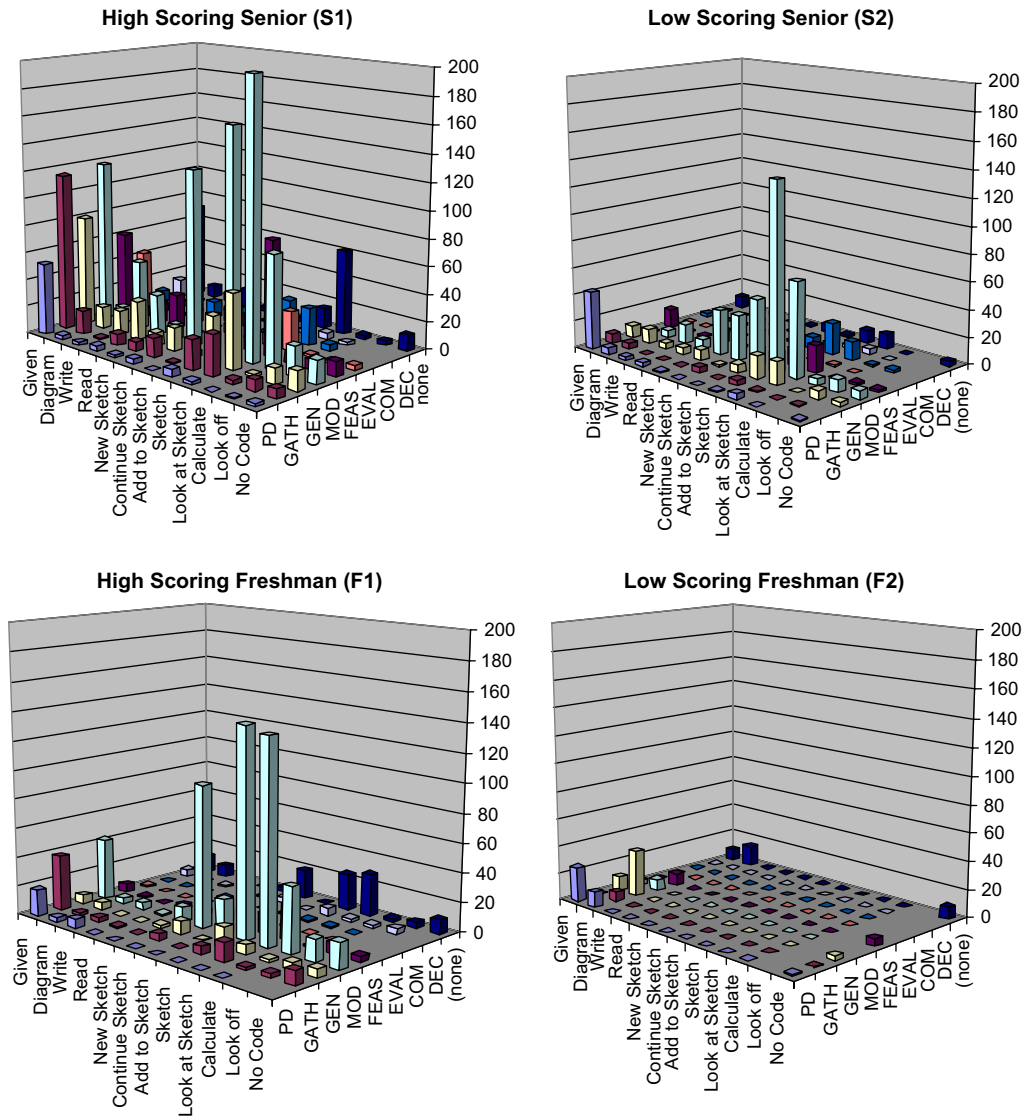


Figure 2 Three dimensional bar charts for all four participants

percent of time in the Developing Alternative Solution stage and progression to the later steps of the design process, evaluation, communication and decision. Participant S1 mainly interacted with given information while defining the problem and gathering information (the Problem Scoping stage) but also used every other form of representation, with the exception of calculations and equations. While spending time in the communication step, Participant S1 primarily created sketches, read

information from the sketch, and spent time creating a written response. Additionally, Participant S1 interacted with the given information, reread written responses, and worked on calculations as part of the communication step. Finally, this student sketched primarily while Developing Alternative Solutions (73% of the time) and a substantial percent (10%) of S1's sketches occurred in the communication step, though only 6.1% of Participant S1's time was spent in communication.

3.2 Case study S2: low-scoring senior

Participant S2 produced a solution of lower than average quality (0.39). In other ways, this participant did not differ dramatically from the average performance for seniors (see Table 2). While Participant S2 did not cover the design activities quite as thoroughly as Participant S1, Participant S2 did engage in every representation activity at some point and did spend time in every design activity step. In many ways, Participant S2 exhibited behavior similar to Participant S1. In the communication step, Participant S2 mainly created sketches and read information from the sketches. Participant S2 did not interact with the given information while in the communication step as much as Participant S1, but did interact with given information somewhat in addition to interacting with the diagram, creating written responses, rereading written responses, making calculations and thinking without focusing attention on any material. Like Participant S1, most sketching (80%) took place while Participant S2 spent time Developing Alternative Solutions, though a notable amount (11%) coincided with the communication step. Finally, the time that Participant S2 spent in Problem Scoping stage included time allocated to each representational activity except calculations, though this student attended to the given information far more than the others.

3.3 Case study F1: high-scoring freshman

Participant F1 received a high quality score (0.53) despite spending less time than average solving the problem and spending little time in the evaluation step (see Table 2). This participant did, however, meet many of the constraints and spent a higher than average amount of time in the decision step and a higher than average percent of time in the Developing Alternative Solutions stage.

Despite spending relatively little time solving the problem, the participant did spend time in each of the eight design activities and did spend time sketching in each activity except problem definition. While engaged in problem definition, this participant interacted with given information, written information and the diagram. Interacting

with given information also dominated the gathering information activity, though sketching was one of the other major representational activities that the participant performed as part of this design step. Additionally, for Participant F1, sketching was one of the most prevalent representational activities in the other six design activities.

The other measure of interest for the freshmen is Evaluation, since time in evaluation was correlated with quality of solution. The only instance that this participant spent time in the evaluation step, the participant also Sketched (in addition to looking at a 'given' piece of information). Finally, a high percentage of this participant's sketches (80%) were also made in the Developing Alternative Solutions stage. This is not surprising since this participant spent a similar percent of total time in the Developing Alternative Solutions stage.

3.4 Case study F2: low-scoring freshman

Participant F2 was first chosen to represent poor performance—a freshman who received a low quality score (0.19), spent little time solving the problem, spent no time in evaluation or in decision, met few constraints and spent a smaller than average percent of time in the Developing Alternative Solutions stage (see Table 2). However, this participant is also interesting because of the lack of both sketching and writing behavior. This participant essentially produced no solutions other than those verbally recorded as part of the experimental procedure. The only two representational activities that Participant F2 engaged in were Reading Given Text and Looking at Given Diagram, the two representations provided for the participant. Participant F2 spent time in only the first five of the eight design activities—spending no time at all in evaluation or the Project Realization stage. This student did not create any visual representations, but did use the diagram for information for each design activity, most frequently for generating ideas (41% of the time). Though Participant F2 used the given information more than the diagram while defining the problem, this student used the diagram more than the given textual information for the other four design activities and used only the diagram while performing feasibility checking.

3.5 Comparisons across freshmen and seniors

While we cannot come to any conclusions about differences between freshmen and senior engineering students based on four examples, we can note some trends that we might later investigate with a larger dataset. The two seniors exhausted the combination of design activities

and representation activities to a greater degree than did the freshmen. This is especially true for Participant S1 who performed nearly every design activity while using each and every possible representation. There are consistent gaps at the intersection of Adding to Sketch and Problem Definition as well as Calculation and Problem Definition for all participants. There are also gaps for the intersections of Communication with representation activities and Decision with representation activities that are consistent for the freshmen but not for the seniors.

3.6 Comparing across seniors

In the initial discussion of the [Atman et al. \(1999\)](#) study, it was noted that for the freshmen, many design activities correlated with quality of solution while for the seniors, few variables correlated with quality of solution. The two seniors presented in this paper—Participant S1 and Participant S2—are examples of this. Despite having very different quality scores, they met nearly the same number of constraints, spent a similar amount of time solving the problem, and spent similar amounts of time in each design activity. Notable exceptions are that Participant S1 spent more time gathering information and evaluating solutions than did Participant S2. The only other main difference in design behavior is the use of representations. As noted previously, Participant S1 exhausted nearly every combination of design activity and representational activity. In particular, this student covered the intersections of Gathering Information with every representational activity and Evaluation with nearly every representational activity. Participant S2, in contrast, engaged in relatively few representational activities while Gathering Information and Evaluating alternatives. This suggests that extent of use of representations may possibly explain the differences in Participant S1 and Participant S2's design behavior—the differences in amounts of time spent Gathering Information and Evaluating alternatives—as well as differences in quality of solution. The latter is particularly interesting because to date there are few design measures that predict quality of solution. Therefore, a future opportunity would be to continue the current analysis on the remaining protocols to analyze correlations between representational behavior and quality of solution for the senior engineering students.

4 Discussion

The four case studies illustrate that the use of representations during design varies across engineering students. Each participant exemplifies important differences in extent of engineering coursework, final quality scores, and important features of student design processes. The three

participants who chose to create representations—in the form of written responses, sketches and calculations—performed each of the coded representation activities and also spent time in each of the eight design steps. That is, these three participants progressed to the later steps of the design process. How these three students distributed their time amongst design activities and the extent to which they used each type of representation varied, as well as the way they used particular representations while spending time in particular design activities. The finding that these three students did progress to the later steps is important because it is a documented problem that some students are unable to progress past information gathering into solution generation (Christiaans and Dorst, 1992) and that students who do not progress into the later steps tend to produce lower-quality solutions (Atman et al., 1999).

Despite the variation, some patterns emerge. In nearly all cases, each representation activity coincided with Modeling more than the other seven design activities. This is not surprising, since most participants allocated the greatest percent of time to the Modeling step (Atman et al., 1999). Another pattern we might have expected is that most participants (all except Participant F2) use given information more than engaging in any other representational activity during the Problem Scoping stage. What is more interesting is that those participants who sketched, sketched in the Problem Scoping stage. This resonates with Römer et al.'s (2000) finding that sketching supports problem formulation. The findings of the current study replicate Römer et al.'s (2001) finding that sketching supports communication as all three participants that engaged in the communication step either created a sketch while doing so or spent time looking at a sketch. Finally, two of the three participants who made decisions as part of their design process both sketched and looked at their sketches while doing so. For these two participants, Sketching and Looking at Sketches appear to be the primary representational activities for most of the design steps. This suggests that sketching supports not only Problem Scoping (or problem formulation) and communication, but each and every design activity.

This brings us to the participant who did not choose to create any representations, and instead relied solely on those provided by the experiment administrator. This participant spent little time on the problem and did not progress to the final design steps. Because this participant did not create any solution aside from the ideas captured by the verbal protocol, it is not surprising that this participant did not communicate a final design. However, this also reinforces the previous suggestion that sketching supports communication. The four case

studies presented here show that every participant who spent time in communication used a sketch in some way and that the only participant who did not use a sketch did not spend time in communication.

As for decision and communication, the other design activities overlooked by Participant F2, it is more difficult to draw similar conclusions. For example, Participant S2 spent time making evaluations and making decisions without using sketches. Instead, S2 relied on the given information. However, Participant S1 and Participant F1 relied heavily on their sketches throughout the later three design steps, suggesting that the use of sketches is important for progression in the design process.

Participant F2's behavior elicits two questions: why did this participant choose not to create a sketch? Would the design behavior (both in terms of representational activity and design activity) have been different had the experimenter not provided a diagram? It is possible that these two questions can both be answered by saying that the participant did not sketch because a picture had been provided. Had the diagram not been provided, the only possibility for visual data would have been to create a sketch. It is unknown whether the absence of a diagram would have elicited sketching and the behavior supported by it—namely, progression to the later steps of the design process. What is known is that while this participant did not create any external representations, the participant still interacted extensively with the given graphic representation.

These case studies also offer some insight into engineering education. From these case studies, particularly the results presented in [Figure 2](#), we can identify representation activities associated with design activities known to contribute to or correlate with higher quality solutions. This suggests that supporting these representational activities in design classrooms and providing opportunities for students to develop representation skills might be beneficial for the students. For example, educators could teach students how to sketch and gather appropriate information from written texts. The question becomes: which representation activities to support and during which design activities?

The results provide insights for considering answers to this question. We know that those seniors who spend a greater percent of time in Problem Scoping and Developing Alternative Solutions tend to meet more problem constraints ([Atman et al., 1999](#)). We also know that looking at given text and creating sketches are representational activities associated with Problem Scoping and that looking at given text, creating sketches

and looking at sketches are activities associated with Developing Alternative Solutions. Therefore, one opportunity to support students as they learn to design is to include instruction that models the use of textual information and the creation of sketching while in the Problem Scoping phase. Likewise as students are taught to Develop Alternative Solutions, instructors should teach students to use textual information, create sketches, and spend time reflecting on created sketches.

In a similar manner, we can refer to [Figure 2](#) for other pairings of design activities and representational activities. Focusing on the row for a specific design activity allows the reader to see which representation activities might best support that design activity, and focusing on the row for a specific representation activity shows which design activities are most likely to be supported by that representation activity. From S1, S2 and F1 we see that if an instructor hopes to teach students to make calculations, presenting the material in terms of modeling a design solution is a natural context. From S1 and F1 we see that if an instructor wants to encourage students to make design decisions, the instructor might teach the students to use the problem statement and other given textual information as an aid to making decisions or to look at sketches the students have already created. Finally, from F2 we see that an instructor can help students practice feasibility analysis skills by presenting students with a diagram in addition to a written problem statement.

5 Conclusion

Across our four case studies, external representations supported every aspect of students' engineering design process. Specifically, most students created and used sketches as one of the main representational activities throughout the design process. Sketching particularly supports the communication design activity. Sketching also played a large role in the Problem Scoping stage, though our participants relied on the given information to an even greater extent.

The findings also highlight implications for design education. One example is the contrast between the participants who created external representations as part of their design process and the one who did not. The use of external representations by the students examined in these case studies suggests that it is for good reason that students are encouraged by many instructors to create drawings while solving problems. More broadly, these results suggest that (a) we could support

representational activities in design classrooms and (b) we could support opportunities for students to develop representation skills.

This analysis shows interesting relationships between greater use of representations, most notably sketching, and more sophisticated design processes and products. However, an analysis based on a set of four case studies is too small to allow generalization of the results. The results do not provide an explanation as to whether a representation activity actually causes the student to spend time in a design activity or if a design activity leads a student to spend time in a representation activity. We are also limited in our ability to explain how or why sketching might support so many design activities. Further investigation should be undertaken to determine the prevalence of these findings and to further establish a relationship between the creation of external representations and verbal design activities. Previous work, however, offers some insight into why sketching supports higher quality solutions. For example, [McGown et al. \(1998\)](#) suggest that sketching can make concrete an entity that has been conceived of in the imagination, help the designer remember the physical nature of physical environments and objects, allow the designer to try out a new idea quickly and inexpensively and allow the designer to examine and reflect on a design idea.

As work continues in design research, we will likely see more explanations of why and how sketching and other representations support both student and expert designers. For example, we might like to see an exploration of how students or practicing designers use representations in their natural settings to gain rich insights into how designers actually use representations, in contrast to the prescription of how designers *should* use representations. It is our hope that the research presented in this paper will inform not only additional research studies but also the creation of instructional activities pairing representational activities with design activities and that the further exploration of external representations will further improve engineering design education.

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Appendix A. Example sketches

