The Design Processes of Engineering Educators: Thick Descriptions and Potential Implications

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The goal of this paper is to shed light on the design strategies of engineering faculty. While there already exists a large body of research in understanding the design processes of students and practicing engineers, less work has been done to understand the design processes of engineering educators. However, the engineering educators offer students their first introduction to engineering design. By examining the design processes of engineering faculty members, we can gain a new perspective on engineering design practices in addition to insight into students' learning of design. Here we present both quantitative and qualitative data concerning the design processes of four engineering faculty members. The results suggest that faculty designers' processes are very diverse. We offer some implications of the variety in educators' design processes with an emphasis on possible teaching opportunities and challenges suggested by the data.

Anyone who has been involved in design education realizes the complexity entailed. We can start to unpack this complexity by turning to relevant research in education. Such research suggests that the effectiveness of educational interventions is influenced by factors such as the varied difficulties learners experience when learning in a specific domain, the demands associated with gaining particular types of knowledge, the variety of potential learning outcomes in a domain, the challenges students often have in moving from one conception of a subject matter to another, the resources available to support the instruction, and the conditions under which different teaching strategies work (e.g., Sinatra and Pintrich 2003; Bransford et al. 1999). In the context of design, these observations point to the importance of understanding a) the strategies and knowledge expert designers draw upon, b) what the development of such strategies and knowledge looks like, and c) when different types of instructional approaches such as studio teaching or project-based teaching are appropriate. The design community is already exploring these issues and other related issues (e.g., Cross and Clayburn Cross 1998, Newstetter and McCracken 2001, Goldschmidt 2002).

Teacher knowledge is another factor that impacts the effectiveness of educational interventions. Recent research has drawn attention to the types of knowledge that educators bring to their teaching and the impact of this knowledge on the effectiveness of the teaching. For example, some researchers have compared the strategies used by expert and novice teachers in order to illustrate the types of unique knowledge that experts bring (e.g., Livingston and Borko 1989). Other researchers have focused specifically on pedagogical content knowledge—an educator's knowledge about the difficulties students encounter when learning something and the teaching strategies that can be used to address the difficulties (Shulman 1987, Bullough 2001). Still other researchers have looked at the beliefs that educators have about the subject matter and students they are teaching (Wideen, Mayer-Smith and Moon, 1998).

These observations on the importance of teacher knowledge suggest that it might be beneficial for the design research community to explore the knowledge of its design educators. One starting approach would be to characterize the design processes of design educators. We could then use this information to explore how the educators' design processes compare with the design processes of their students, of design experts, and even of the textbooks that they use for teaching. For example, previous studies of entering and graduating students' design processes have suggested that student processes are quite variable (Atman and Turns 2001). Does this finding apply also to design educators, or do the educators have more standardized approaches to design? In order to ask this question and other potential questions, it would be useful to have educator design processes characterized in a manner that is consistent with a characterization of students and also characterized in some detail.

In this paper, we begin a discussion of the design knowledge of design educators, guided by the factors mentioned above.
Overall, through the paper, we seek to address three questions:

1. What do the design processes of engineering educators look like? Specifically, are the design processes consistent across the educators, or are they highly variable, as are the students in the previous studies?
2. What teaching ideas or teaching challenges are suggested by these results?
3. What additional research is suggested by these results?

Specifically, we report on the design processes of four engineering educators who completed a design task under laboratory circumstances. Because this task was the basis for an earlier experiment exploring the design processes of entering and graduating engineering students, the educator and student results are directly comparable. In our presentation, we characterize the design processes of the educators along a wide variety of dimensions, in order to provide a thick description of their activities.

1. Methods

In this study we asked four educators to design a playground for a fictitious neighborhood. This problem was a variation of a problem developed for a term project in an engineering course (Dally and Zhang 1993). The instructions for the problem are presented in Figure 1. At any point during the solution process, the educators were able to ask the experiment administrator for information about the neighborhood, budget, materials, safety and many other factors relevant to playground design.

In some instances, however, the participants requested pieces of information beyond the scope of the administrator's box of information.

The four educators represented three engineering departments: industrial engineering, mechanical engineering and nuclear engineering. Three were in their early 30s—32, 34 and 35—while the fourth was 62. Three of the designers were male and one was female. Three of the educators had experience working in industry.

> You live in a mid-size city. A city resident has recently donated a corner lot for a playground. You are an engineer who lives in the neighborhood. You have been asked by the city to design equipment for the playground.
>
> You estimate that the children who usually use the equipment will range in age from 1 to 10 years. However, occasionally some adults will also use this equipment. From the amount of space you have in the park, you estimate that you should design equipment to keep 12 children busy at any one time. You would also like to have at least three different types of activities for the children.
> The equipment must:
> - be safe for the children
> - remain outside all year long
> - not cost too much
> - comply with the Americans for Disabilities Act, so handicapped children will be able to play also
>
> The neighborhood does not have the time or money to buy ready made equipment pieces. Your design should use material that is available at any hardware or lumber store. The equipment must be constructed in under 2 months.
>
> Please explain your solution as clearly and completely as possible. From your solution, someone should be able to build your playground without any questions. The administrator has more information and tools to help you address this problem if you need them. You must be specific in your requests. For example, if you would like a diagram of the corner lot for the playground equipment, you may ask for it now. If you think of any more information you need as you solve the problem, please ask.
>
> Remember, you have approximately 3 hours to develop a complete solution. The administrator will inform you about how much time is left as you work.

Figure 1: Problem text

Three of the educators solved the problem in a laboratory setting at a university and one solved the problem in a private home setting. The educators were asked to think aloud as they solved the problem (Ericsson and Simon 1993, Atman and Bursic 1998). They solved two problems to practice thinking aloud before solving the three-hour playground design problem. If they fell silent during the experiment, the experiment administrator encouraged them to keep talking. After they completed their design, they read and commented on a description of the design process and completed a questionnaire. All four educators were audiotaped while solving the problem, and the educators who solved the problem in the laboratory setting were also videotaped. These same procedures were used in a previous study investigating students' design behavior (Atman et al 1999); we will mention some results of the study of the students in the discussion section.

Transcripts of the tapes then form the data with which we performed a verbal protocol analysis (VPA) to identify and describe the design processes the educators used. Each transcript was segmented into small units of text that could be coded with four predetermined coding schemes. Both segmenting and coding were performed by two independent analysts, and all differences were resolved. The four codes categorize aspects of the design processes that were employed, including design step, activity, information processed (e.g., budget, material costs, etc.) and object (e.g., slide, benches, landscaping, etc.). A description of the codes for design step and activity is presented in Table 1. The coded segments were then used as a basis for describing the design processes of the educators in terms of amount of time per code and transitions between codes. As shown in Table 1, the design steps were grouped into three design stages (Problem Scoping, Developing Alternative Solutions and Project Realization); this allowed us to also measure amounts of time per stage and transitions between stages.

Table 1: Design step and activity coding scheme

Design Step	**Description**
Problem Scoping:	
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
Developing Alternative Solutions:	
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
Project Realization:	
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
Activity	**Description**
Read	Read either the problem statement or information that has been gathered
Constraints	Identify, deal with or meet problem constraints
Assumptions	Make implicit or explicit assumptions
Calculate	Make calculations
Other	Perform another design activity, such as request information that is unavailable

Finally, the educators' solutions were scored for quality of solution. The quality of solution score is comprised of three elements. The first was a set of forty criteria that each solution should meet. The first seven criteria were based on the specific constraints given in the problem statement, and the remaining criteria were based on design criteria that all playground designs should meet, as outlined in Play for All (Moore, Goltsman and Iacofano 1992). The second part of the quality score is based on whether the designer met additional criteria that were appropriate for the participant's particular design. The final part of the score was based on ratings for diversity of activities, aesthetics, protection from injury, uniqueness and technical feasibility. These ratings were scored on a scale from one to five.

2. Results from educators

A detailed description of the data from these four subjects is available in a technical report (Cardella et al. 2003). In this section we present a subset of the data that allows us to richly characterize the design processes of these four educators. We present this data through five windows: 1) quantitative data presented in Table 2, 2) qualitative data gathered from the participants' transcripts, 3) design activity timelines presented in Figure 2, 4) cumulative time charts presented in Figure 3 and 5) three-dimensional bar charts showing the intersections of design activities in Figure 4.

2.1 Window 1: quantitative data

Table 2 presents summary statistics for the faculty and student designers as well as the outcomes for each individual faculty participant. From Table 1 we see that the four faculty participants spent strikingly different amounts of time solving the problem, ranging from 1 hour 3 minutes to 2 hours 32 minutes. Participant B transitioned between design activities at a much faster rate (7.81 transitions per minute) than the other three participants (1.67, 1.45, 1.67 transitions per minute). We also see that participants A and B each requested 62 pieces of information while C gathered only 5 pieces of information and D requested 12 pieces. Additionally, C and D did not explicitly request this information from the experiment administrator—instead, C and D made assumptions about the information that they needed (for example, instead of asking the administrator if supervision is available, C assumed that there would be people around to supervise play).

2.2 Window 2: qualitative data from transcripts

In this section, we present qualitative data from each participant's complete transcript, which includes the protocol for the playground design as well as each educator's reflection on the design process. Additionally, we have incorporated data from the educators' questionnaires.

Participant A: Methodical and Comprehensive
Participant A was a 32-year-old female faculty member in an industrial engineering department. A had worked as a systems analyst for nine years before beginning the faculty position. This participant used the full three hours and would have liked more time; even so, A's final solution

Table 2: Overview of results

	Entering students	Graduating students	Faculty	A	B	C	D
Design Step							
Problem Definition	5:08	4:10	6:17	6:46	3:14	11:03	4:06
Gather Information	13:49	14:19	15:05	38:38	14:02	3:05	4:34
Generate Ideas	10:08	9:22	33:15	7:32	14:54	1:32:13	18:22
Modeling	1:02:41	1:05:21	33:59	1:13:58	31:34	7:15	23:09
Feasibility Analysis	7:48	9:42	12:49	14:21	12:49	16:33	7:33
Evaluate	1:24	1:58	1:19	0:59	1:34	1:56	0:45
Decision	0:24	0:45	0:19	0:05	0:49	0:00	0:23
Communication	2:38	4:50	6:13	10:24	0:53	8:35	5:01
Total Time (hr:min:sec)	1:44:00	1:50:26	1:49:31	2:32:43	1:19:49	2:20:40	1:03:53
Problem Definition	6.1%	4.0%	5.7%	4.4%	4.1%	7.9%	6.4%
Gather Information	12.4%	14.1%	13.1%	25.3%	17.6%	2.2%	7.2%
Generate Ideas	11.7%	9.1%	29.5%	4.9%	18.7%	65.6%	28.8%
Modeling	55.8%	57.3%	32.4%	48.4%	39.6%	5.2%	36.2%
Feasibility Analysis	9.7%	8.7%	12.3%	9.4%	16.1%	11.8%	11.8%
Evaluate	1.3%	1.7%	1.3%	0.4%	2.0%	1.4%	1.2%
Decision	0.4%	0.8%	0.4%	0.1%	1.0%	0.0%	0.6%
Communication	2.6%	4.2%	5.5%	6.8%	1.1%	6.1%	7.9%
Design Stage							
Problem Scoping	18:57	18:29	21:22	45:24	17:16	14:08	8:40
Dev Alt Solutions	1:22:01	1:26:23	1:21:02	1:36:50	1:00:57	1:58:07	0:49:49
Project Realization	3:02	5:35	6:32	10:29	1:42	8:35	5:24
Problem Scoping	18.4%	18.1%	18.7%	29.7%	21.6%	10.1%	13.6%
Dev Alt Solutions	78.5%	76.9%	75.4%	63.4%	76.2%	83.9%	78.0%
Project Realization	3.0%	5.0%	5.9%	6.9%	2.1%	6.1%	8.5%
Transition Behavior							
Step Transitions	114.9	186.4	285.8	256	548	232	107
Stage Transitions	70.5	105.0	181.3	186	326	158	55
Transition Rate (tran per min)	1.2	1.8	3.2	1.7	7.8	1.5	1.7
Stage Tran Rate	0.7	1.0	1.8	1.2	4.0	1.1	0.9
Solution Score							
Constraints Met	5	4.9	5.8	6	6	5	6
Fulfilment of Criteria				14/40	18/40	13/40	18/40
Ratings				18/25	18/25	14/25	14/25
Supplementary				19/35	16/46	1/20	2/29
Quality Score	0.45	0.51	0.43	0.54	0.51	0.31	0.36
Information Requests							
Number of Info Requests	14.2	25.0	35.3	62	62	5	12
Assumed	2.8	9.3	18.0	31	24	5	12
Explicit	11.4	15.8	17.3	31	38	0	0
Number of Categories Covered by Explicit Requests	3.4	5.1	4.3	8	9	0	0

was complete. A wanted to provide a precise solution that included everything that a contractor would want or need to build the designed playground. A conscientiously gathered a great deal of information, and then proceeded with the design. The designer rarely backtracked or changed a decision.

Two main themes guided A's design: user-centered and precision. Before even considering any playground equipment, A gathered information on the types of activities the user group (children and parents) wanted. All throughout the process of designing the playground, A thought about what the contractor would need in order to build the playground. As for precision, A spent a great deal of time determining dimensions and costs. A also used a matrix to check problem requirements and prioritize and arrange equipment. The designer rarely designed at a more abstract level—considering various thematic arrangements for the playground, or considering different configurations or collections of activities.

A's final solution consisted of a scaled layout diagram, costs for each piece of equipment (for example, A's swings cost $93.71 each) as well as a breakdown of the costs for each of the elements of each piece of equipment, plans showing dimensions for each piece of equipment and a schedule showing when each piece of equipment would be built. For the final layout, A cut out pieces of paper to represent the different pieces of equipment and then arranged the cut-outs within the lot space. The design does not include many elements beyond the list from the neighborhood survey (the user survey was one of the pieces of information that the participant could request; it listed the six most popular pieces of playground equipment). However, A conscientiously sought to meet the users' needs throughout the design process. Participant A wanted to provide a precise solution that included everything that a contractor would want or need to build the designed playground.

Participant B: Information-Gathering Iterator

Participant B was a 34-year-old male professor of mechanical engineering with experience working in industrial departments at four different companies. Unlike the other three faculty participants, B solved the problem at home rather than a laboratory setting. B interpreted the task as requiring a detailed, precise solution.

Like A, B was an implementer who gathered extensive amounts of information at the beginning of the design process and then continuously modeled solutions. B in particular operated under an overarching strategy of information optimization. This faculty member began the design process by asking for 56 pieces of information (including both information that was and information that was not available) on the surrounding area, the playground lot, and the environmental conditions before saying:

> Okay, let's see, I'm about ready to design this…

B then used the information to define the problem as opposed to creating B's own problem definition. This participant started off trying to establish then re-establish the design constraints and interpret the rules.

Additionally, this participant was very concerned with understanding the environment, and used this as a second main strategy. Finally, B noted early on in the design process:

> …it's going to be very iterative.

In fact, B made more than twice as many transitions among design activities (548) than the other participants (256 for A, 232 for C and 107 for D) and B had a much higher transition rate (7.81 transitions per minute) than the other faculty participants (1.67, 1.54, 1.67 transitions per minute).

B continued working until detailing a final design. Like A, B included a scale on the diagram. Participant B produced a neat, organized design.

Participant C: Idea Generator
Participant C was a 35-year-old male assistant professor of Mechanical Engineering. He related the problem to his experiences with his 2 year-old child. This designer spent 2 hours, 20 minutes solving the problem but stopped before producing a detailed design.

Early in the design process, C requested a piece of information that was not available; this was the only time that C requested information. This first interaction possibly led C to believe:

> …there's a lot of information that was inaccessible… for example, price information and material.

C generated many ideas and then invested only 7 minutes in modeling the design alternatives.

C displayed one of Goel and Pirolli's traits of expert designers: reversing the direction of transformation (Goel and Pirolli 1992). C wanted to include the buildings that surrounded the lot in the design of the playground. Once C realized this desire, C manipulated the problem to try to incorporate the surrounding buildings.

Another distinguishing characteristic about C's design process was the introduction of additional constraints. From the beginning of the protocol, C wanted to design more than an ordinary playground—C wanted a learning experience in which children would learn to become participating members of society, co-operate with each other to accomplish goals and challenge themselves both cognitively and physically. C wanted to design a community experience where children of all ages played and learned together. C met many of the problem's stated requirements, but extended much more time trying to meet the requirements he himself developed.

Finally, C's process was very structured, and C expressed awareness of decisions to engage in specific activities. For example, early in the design process, C referred to the constraints C needed to meet and the process of acquiring materials and said,

> …again, I think this is something I'll work on a little later.

A few minutes later C decided:

> Okay, so, well, I've picked out a starting place for myself. I'm going to, as I'm talking, as I write, I'm going to continue to glance back and forth at the map.

In the end, this faculty member did not produce a very detailed final design. C thought of equipment ideas but did not specify how to build the equipment. This led to a low quality score, since C did not fulfill the supplementary criteria, which were based on equipment specifications. However, Participant C's design did include playground equipment and activities that deviated from the user-defined list, such as a post office where children can write letters and then deliver them to mailboxes.

Participant D: Rich Life Experiences

Participant D was a 63-year-old male practitioner who taught some nuclear engineering courses. This participant commented on having participated in neighborhood playground projects and also described qualities of four different playgrounds while debriefing the design experience with the administrator. D completed the playground design in just over one hour and chose not to provide complete design details. D knew where he would have gone if he had continued to design (to CAD or construction paper models), but consciously decided not to do this.

The designer focused primarily on one solution, and drew upon some very clear domain knowledge (e.g., what is required in a building permit), but did not explicitly request much information. The experiment administrator's explanation for this is that the participant was:

> very familiar with many things in the box [of information]: drew a lot from his expertise.

Like C, D displayed a self-awareness of the activities that he chose to engage in:

> …let's go back through and see now, we've got, we've got the general design done, we haven't now, sat down and actually laid out in, in detail…

The designer addressed a collection of boundary/interface issues—what would make the design buildable by the community (and what could be assumed about the community's building ability), supporting additional fund raising, and thinking about the fence around the property. The participant visualized safety issues and accounted for them while designing.

The designer also gave a great deal of attention to costs—but did not end up meeting the cost requirement for the quality coding. However, D did talk about how to meet cost if the final solution was over budget. D also talked about the cost of construction, about hiring a contractor, about the potential need for fundraising. However, this designer missed some points for his quality score because he did not devise a final budget or estimate the costs of specific pieces of equipment. The designer's decision to stop before producing detailed design specifications also contributed to a low quality score.

Participant D designed at a higher level of abstraction, rarely getting down to the level of dimensions/costs. In contrast, A rarely designed at an abstract level (i.e. considering different configurations or collections of activities). While C and D can be characterized as idea generators operating on an abstract level, both A and B were implementers who gathered extensive amounts of information at the beginning of the design process and then continuously modeled solutions.

2.3 Window 3: design step timelines

As the previous section suggests, one striking result was in the variability of the design processes across the participants. The design step timelines in this section provide additional insight on this variability—they display each participant's allocation of time throughout the design process. The timelines were created using MacSHAPA (Sanderson et al. 1994). Time is presented from left to right, and time spent in each design step is indicated horizontally. As a participant spent time in a design step, a block is placed on the line for that step. The width of the block represents the amount of uninterrupted time that the participant spent in the step. Wider blocks suggest that the participant stayed in one step rather than transitioning between steps.

The step timelines (see Figure 2) show that for the most part, all four faculty participants spent time in each step all throughout the design process. This is in contrast to some of the student designers who failed to spend any time in the activities of Evaluation (EVAL), Decision Making (DEC) or Communication (COM). While the faculty participants spent less time in these steps as they did in the other five steps, the faculty participants did spend some time in these activities. Most notably the faculty participants spent time in communication throughout their design processes. Returning to Table 1 we also see that the faculty spent a higher average amount of time in Communication than did the students.

The timelines also show that the faculty participants often transitioned between steps. This is notable since our previous studies with student designers have shown that transition behavior is correlated with quality of solution. Most of the tick marks are narrow, showing that a small amount of time was spent on this activity before the faculty participant transitioned to a different activity. One exception is noticeable in C's timeline: C often spent long periods of time Generating Ideas (GEN). That is, C would start to generate ideas and would continue to do so for an appreciable amount of time before switching to a different activity. The noticeable chunks of time devoted to generating ideas in C's timelines also draw attention to the fact that C spent far more time generating ideas than in the other seven steps.

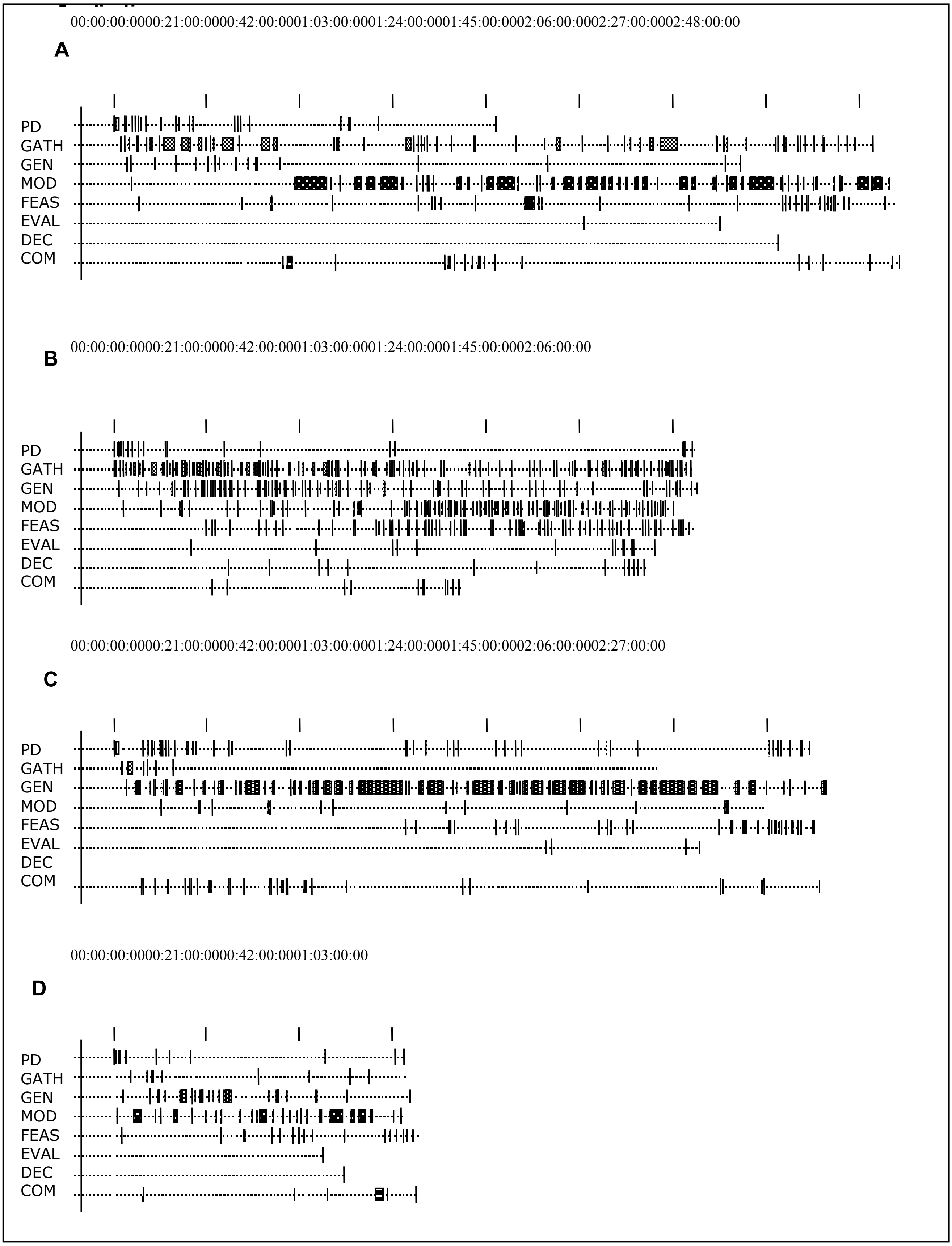

Figure 2: Step timelines

Another difference evidenced by the timelines is the difference in information gathering behavior. The timelines for A and B show extensive

Gathering Information (GATH) throughout their design processes. In contrast, the timelines for C and D show limited Gathering Information, happening more at the beginning of the design process than the middle or end. These differences in information gathering behavior that are apparent in the timelines support the observations in the previous descriptions of these four participants.

Finally, the timelines can be compared to timelines of students' design behavior. While we are unable to offer a full comparison in this paper, it is worth noting that the timeline for participant A is qualitatively similar to a timeline for a high-scoring graduating student.

2.4 Window 4: cumulative time charts

The cumulative time charts in Figure 3 are comprised of eight different lines—one for each of the eight design steps. The lines show how much cumulative time each participant has spent in a particular design step at certain points during their design processes. Cumulative time charts show when designers divide their time equally between design steps as well as when particular steps overtake the process.

For each of the four participants, there is at least one activity that the designers tended to spend more time in—that is, an activity that seemed to dominate the designers' process. In addition to showing when particular activities begin to dominate the participants' design processes, the cumulative time charts show when the dominant activity switches. Modeling (MOD), Gathering Information, and Generating Ideas were the most likely activities to be dominant, though the combination varied by participant. The cumulative time charts also show that while Feasibility Analysis (FEAS) did not dominate any participant's design process, Feasibility Analysis did peak in the last 10-20% of the design process for each participant.

For each of the four participants, once the designer started to spend more time Modeling, the designer began to spend less time Gathering Information. For example, until 40% of the way through the design session, Participant A spent more time Gathering Information than engaging in any other activity. However, at 30% of the way through, the amount of time allocated to gathering information began to decline and the amount of time allocated to Modeling began to increase. For the remainder of the process, in the graph we see the Gathering Information line level off and the Modeling line continue to rise.

In this example, we saw that at a point approximately one third of the way through A's design process, the dominant activity for A switched from Gathering Information to Modeling. We see a similar change in dominant activity for D—from Generating Ideas to Modeling. For C, on the other hand, only one activity really dominated the design process—Generating Ideas. Finally, for B, we see that Gathering Information dominated the process at first and then Modeling dominated the latter portion of the design process.

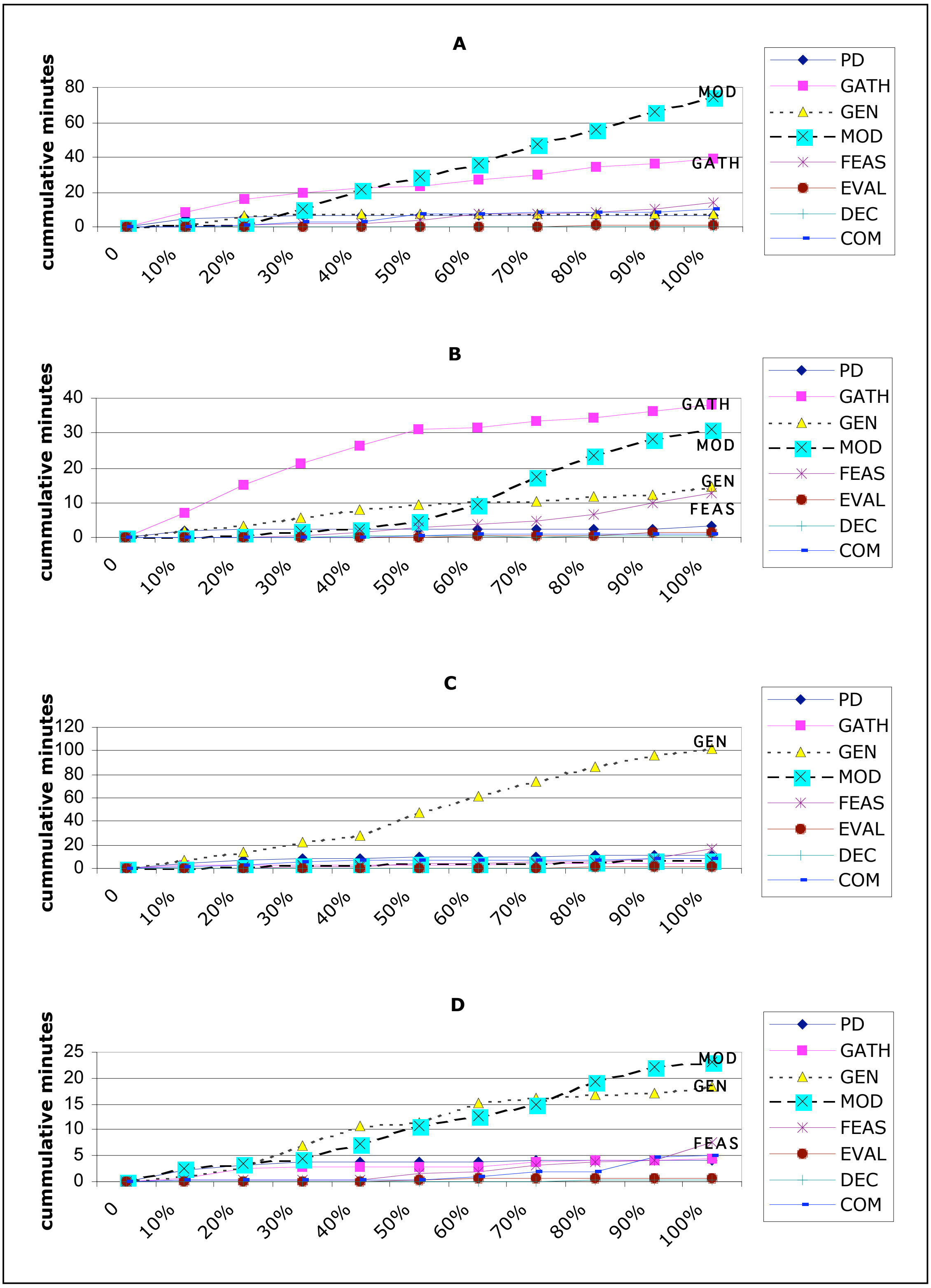

Figure 3: Cumulative time charts

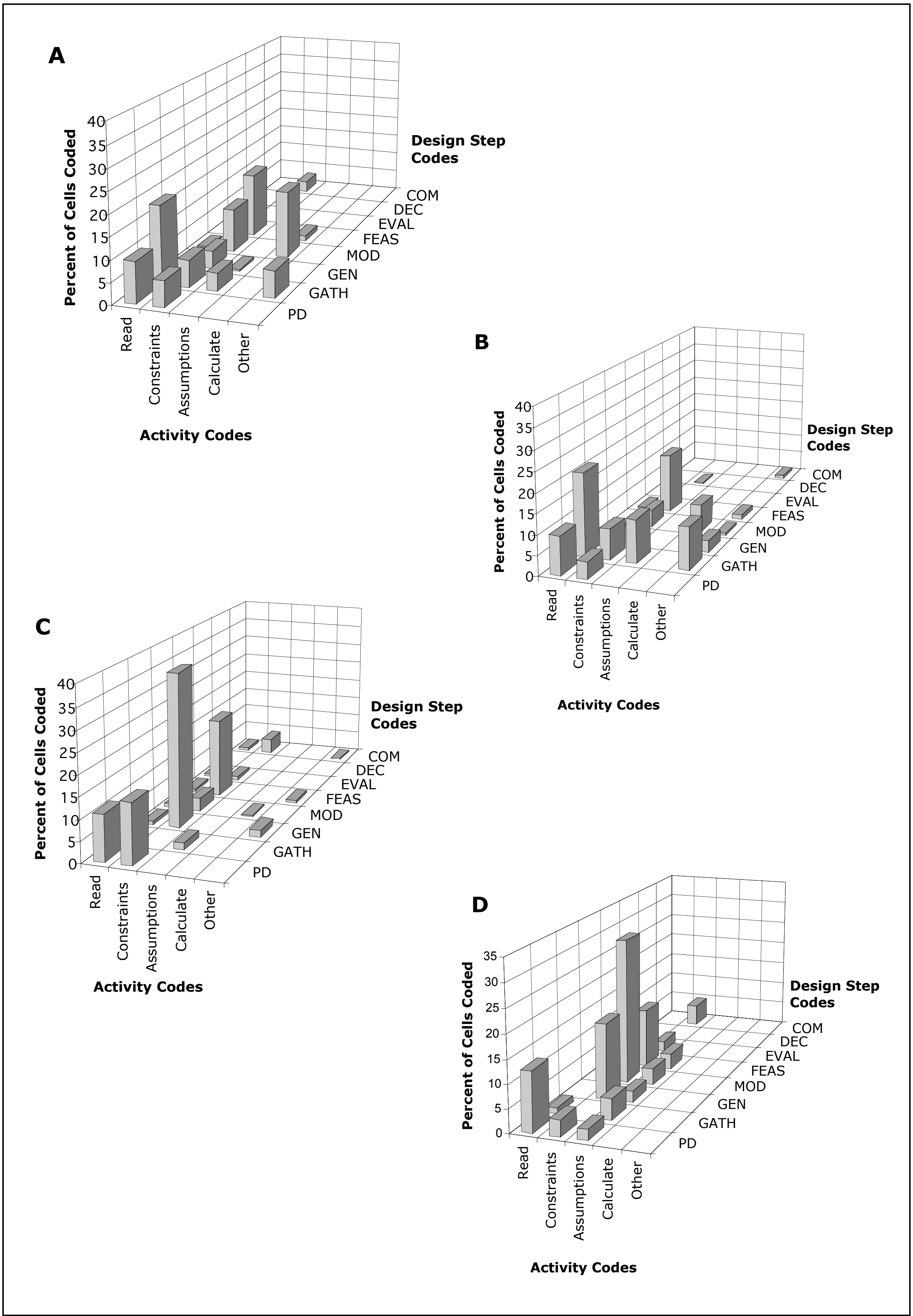

Figure 4: Three-dimensional bar charts

2.5 Window 5: three-dimensional bar charts

The three-dimensional bar charts represent a detailed matrix of design process variables (Figure 4). Episodes of time spent in each design step are shown divided among design activities. Each bar represents percentage of total time spent at the intersection of a design step and a design activity. Further discussion of each of these representations can be found in Chimka and Atman (1998).

The three-dimensional bar charts show that each educator covered approximately half of the possible intersections of design steps and design activities. Across the four faculty designers, Modeling and Feasibility Analysis co-occurred with each of the five design activities. Problem Definition (PD), Gathering Information and Generating Ideas co-occurred with most of the design activities—all except Calculate. However, the three dimensional bar charts also show that there are some consistent gaps. For example, few activities co-occur with Calculate. Additionally, Decision only co-occurred with Constraints. Perhaps most surprising is the finding that Assumptions was largely limited to Gathering Information. Only D makes assumptions while engaged in Problem Definition, Modeling and Feasibility Analysis.

The three-dimensional bar charts also illustrate the differences in the faculty designers' approaches. We see relatively uniform coverage for designers A and B, with percentages (represented by bars) that are approximately the same magnitude. For C and D, however, we see that some percentages are much greater and some percentages are much smaller than others, suggesting that C and D concentrated their time in specific step and activity combinations. Specifically, C spent a large amount of time Generating Ideas while dealing with constraints while D spent much time Modeling while dealing with constraints. While these two designers spent a large amount of time dealing with constraints, they did not spend any time Gathering Information while dealing with constraints. Returning to A and B, the notable time spent in Constraints is at the intersection with Feasibility Analysis. From this we see an overall difference between the two pairs (A&B and C&D) in how they allocated their time as well as a difference in the way that the two pairs dealt with the problem constraints.

3. Discussion

In this paper, we have sought to characterize the design processes of engineering educators. This information can contribute to the discussion of teaching of design as well as opportunities for research on design. Specifically, we have provided detailed descriptions of the design processes of four designers, and compared these processes using five windows. In this discussion, we return to the questions guiding this paper:

1. What do the design processes of engineering educators look like? Specifically, are the design processes consistent across the

educators, or are they highly variable, as are the students in the previous studies?

2. What teaching ideas or teaching challenges are suggested by these results?
3. What additional research is suggested by these results?

The responses to these questions serve to summarize our results and point to future opportunities.

3.1 What do educators' design processes look like?

In the results section, we characterized the design products and design processes of four engineering faculty. The products of these designers were varied, ranging from a conceptual solution to a detailed solution with cost estimates. The detailed process descriptions draw attention to a wide variety of issues in design: prioritizing criteria (e.g., innovative vs. cost effective vs. fun), stopping rules (e.g., deciding what counts as a solution, a conceptual solution vs. a detailed solution), extent to which individual designers explore alternatives, and determining how to bound a design episode (e.g., Participant D seemed to have been designing playgrounds in his mind for some time).

While the thick descriptions provided us with an opportunity to draw attention to very distinctive qualities of these design processes and products, the representations make it easier to compare the four designers. The step timelines draw attention to the extent of transitioning behavior, which ranges from minimal for one subject to extensive for another. The cumulative time charts permit us to see the dominant activities and when particular activities emerge as dominant. We find that the activities of Modeling, Gathering Information and Generating Ideas to generally represent dominant activities, but not consistently across the designers. Additionally, we find that some activities, such as Feasibility Analysis, were not dominant for any of the designers. Finally, the three-dimensional bar charts make it possible for us to characterize more precisely how time is allocated across various combinations of activities. From this representation, we note that two designers seemed to distribute time somewhat equally across a wide number of efforts while the other two designers seemed to spend more time in a smaller number of efforts.

The bottom line from these characterizations is that the faculty members have diverse design processes. Just like engineering students, faculty are not monolithic.

3.2 What teaching opportunities/challenges are suggested by the data?

These observations about faculty design processes provide food for thought concerning their teaching implications and lead to various additional research questions and hypotheses. For example, we saw that designers C and D were aware of the processes while A and B did not exhibit an awareness of their design processes. We wonder about the extent to which educators in general understand their own design processes. It seems that there may be benefits to be gained by helping educators have a deeper understanding of their processes. We also find that the variability in faculty design processes raises the question, what is the effect of the alignment between faculty design processes and student design processes? In our earlier study on student design processes, fifty engineering students (26 entering students and 24 graduating students) solved the playground problem. Analysis of that data showed that although on average the graduating students spent an equivalent amount of time solving the problem as the entering students, they had higher quality designs and had several interesting differences with respect to their design process variables. The graduating students a) gathered more information, b) with the information covering more categories, c) considered more alternative solutions, d) transitioned more frequently, e) had more iterations, and f) progressed further into the steps of the design process. Additionally, the design processes of the students varied, rather than following a single optimal strategy. The full details of that study can be found elsewhere (Atman et al. 1999, Adams 2001).

We now return to our question on the effect of the alignment between faculty design processes and student design processes. The data suggest that there were faculty members who exhibited design processes resembling the processes of graduating students receiving high quality scores (e.g., large number of transitions, high transition rate, and time spent in all steps including decision and communication), that there were faculty who exhibited design processes resembling the processes of a group of entering students that received low quality scores (e.g., effort concentrated on problem definition, information gathering and generating steps and no progression to the Modeling step), and that there were faculty who exhibited design processes resembling the archetypal entering student (e.g., low transition rate, time concentrated on modeling).

What would happen in the cases where educators teach students who have processes that are similar to the faculty members' design process? Would this facilitate the giving of feedback? Would this facilitate the faculty member's being able to understand what the student is trying to do? One can also ask the opposite question, what happens when faculty work with students who exhibit design processes that are different in character to the faculty members' design processes? In such cases of mismatch, would the faculty member have greater difficulty understanding what the student is doing? Would he/she have greater difficulty in providing advice/guidance? In such cases, do students tend to get lower grades? In general, it seems possible that educators who are particularly successful at teaching design may also be the educators who are attuned to such mismatches and have strategies for dealing with the potentially varied circumstances.

3.3 What additional research opportunities are suggested by the data?

As the preceding comments suggest, this study gives rise to a number of future research question and opportunities. For example, the research suggests ideas for exploring expertise in teaching design. In addition to understanding educators' design processes, we would like to understand educators' teaching processes. Additionally, given that this study explored the design processes of four faculty members, one can ask whether the four processes are representative of engineering faculty as a whole. One can also ask about the extent to which the design processes of engineering faculty members are constant, or vary with problem, context, and knowledge.

Another question raised by this research is how faculty and student design processes compare to the design processes of expert engineering designers—the types of designers we would like our engineering students to become. In this case, we are currently conducting a follow-on study to explore this specific question. We are gathering data from approximately 24 expert designers representing diverse engineering backgrounds and different levels of expertise related to the problem (i.e., expertise in playground design). The data from this study will shed light on this question.

4. Conclusion

In this paper, we analyzed design behavior of design educators—instructors who are representative of the types of instructors for the students who participated in our previous study. We found that the faculty members' design behavior, like the students' design behavior, varied considerably. However, we also discovered some design patterns; for example, Participants C and D both chose to stop designing the playground before reaching detailed designs. In contrast, A and B chose a stopping rule that prompted them to stop work on the problem only after finishing detailed designs. From this study, we have a better understanding of how engineering educators address design problems. Additionally, we have raised questions about possible implications for engineering design education. Finally, this study provides a foundation for future exploration of engineering design expertise.

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