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THE PROCESS OF ENGINEERING DESIGN: A COMPARISON OF THREE REPRESENTATIONS

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ABSTRACT

Graphic representations that show how the design process changes over the course of solving a problem are powerful tools for researchers. This paper presents three such representations—timelines, cumulative time plots, and progress time plots—and describes how they provide insights into the design process of engineers.

Keywords: design process, visualization, visual representation, timelines

1 INTRODUCTION

Engineers today face many new challenges and opportunities as the pace intensifies for gains in knowledge and technological developments, and global and societal problems increase in scale and complexity. With these exciting and daunting demands on engineers, it is imperative that engineering education continue to adapt and refine its methods and curriculum in order to produce the next generations of engineering designers equipped to design solutions to our most pressing problems. The need for competent engineering designers has never been greater and thus the need to understand engineering design processes has never been more urgent. Although increasing amounts of research exist concerning engineering design processes, few studies focus on the design processes of engineering students and the capabilities they must acquire to be effective engineering practitioners. As such, a broad goal is to more closely align the outcomes of engineering education with the needs of engineering practice.

2 PREVIOUS WORK ON REPRESENTATIONS IN DESIGN

Representations play a multifunctional role in design activity. For example, they can capture a designer's current understanding of the problem, provide feedback about strengths and weaknesses of a particular design solution, and communicate ideas and final designs to broad groups of people. Such representations have been the subject of much study. One example is the work by Cardella et al. (2006) that shows how designer's create and manipulate sketches to support all aspects of design activity [1]. Representations used by designers were also the focus of the Fourth International Design Thinking Research Symposium held in 1995 [2]. However, these types of representations are not the focus of this paper. A second type of representation is created from observing designers at work and collecting data and measurements throughout the entire design process. When this data is depicted over time, the resulting representation can provide deep insights into the design process. Researchers can then use such a representation to support their own studies or communicate findings to others.

The design research literature is filled with many types of temporal representations of the design process. One of the most prevalent is the *timeline* in which the elements of interest in the design process are displayed on an axis (generally horizontal) over time (or some variant of time such as a segment or episode of a protocol). Several researchers have used timelines to indicate how designers allocate their time across a set of codes to represent various activities in the design process [3-5]. Others have used timelines to represent how designers use and refer to external objects such as sketches and physical models [6, 7]. Gero and colleagues represent Function, Structure, and Behavior aspects of a design problem over time [8], and Suwa et al. use timelines to display cognitive actions [9]. We describe our own version of timelines in Section 4.1.

Other ways to represent how effort is allocated across a design process also appear in the literature. *Linkographies* are a novel way to graphically represent the links among design 'moves', where a move is some operation that changes the state of the design problem. A linkograph can quickly highlight patterns in the process being mapped [10, 11]. *Transition networks* use a node and arc representation to present how a designer transitions from one design activity to another in their design process [12-14]. Probabilities of transitioning can be represented on the arcs to convey relative frequency of transitions from one activity to another. Another type of representation seen in the literature is the *time plot*. Time plots are line charts in which time or an equivalent property is presented on the x-axis, and the y-axis is a quantitative measure of the design process. Such measures have included the accumulated time in specific design activities [15] and a percentage of how much of a subtask has been completed [8]. We present similar versions of these time plots in sections 4.2 and 4.3. Further review of the literature might identify more types of temporal representations of the design process. Using multiple types of representations is important as each has its own strengths and drawbacks. Applying multiple representations to the same data enables multiple perspectives and insights. A notable example of this is the text *Analysing Design Activity* in which 20 sets of researchers analyzed the same dataset [16]. Ten of the research teams used temporal representations, including timelines and linkographs, which afforded a rich and varied understanding of the design process

3 A STUDY OF THE ENGINEERING DESIGN PROCESS

We have used and refined three methods for graphically representing the design process over time. Moreover, we have applied these representations to a common set of data. This data comes from our studies of the engineering design process and how education and professional experience influence its development. In this section, we review two of the studies: a study of the differences in design processes between freshmen and senior engineering students [17] and a study of the differences between engineering students and professional engineers [3]. Due to the richness of the data from these studies, we were able to repeatedly return to the data and ask new questions

3.1 Study Description

Using a verbal protocol analysis method, we asked participants to think aloud as they designed a playground in a three-hour, individually administered laboratory session. The playground design task was specifically constructed to be a general topic approachable for all participants regardless of level of engineering experience and would also not be in the area of domain expertise for any participant. The design task was completed in a closed room with only a participant and a researcher. The researcher administered the task and answered any questions the participant had, including providing additional information about the playground problem if requested. The researcher also prompted the participant to think aloud if she fell silent for a prolonged period. The participant was given up to three hours to complete the playground design task and could finish early if so desired. All task sessions were audio and video recorded, and were later transcribed. For additional details about the design task and study protocols, the reader should refer to [3, 17].

3.2 Participants

Our studies have compared the design thinking and doing typically exhibited by engineers at three levels: 1) entering freshmen just beginning an engineering major, 2) graduating seniors, and 3) advanced practicing professionals. Twenty-six freshmen and 24 seniors participated in the original Atman et al. (1999) study [17]. All of the freshmen were engineering students who had not yet declared a specific engineering major. Of the 24 seniors, 10 were civil engineering majors, 7 were mechanical engineering majors, and 7 were industrial engineering majors. Nineteen expert engineers participated in the follow-up study by Atman et al. (2007) [3]. These individuals had from 7 to 32 years of experience in their fields and were viewed as experts by their peers. Nine of the experts were mechanical engineers, three were electrical engineers, two were civil engineers, two were industrial engineers, two were systems engineers, and one was a materials science engineer.

3.3 Measurements and Analysis

The rich verbal protocol method allowed for multiple types of data analysis and measurements. For reasons of relevance and space, only two are discussed here: design activity coding and quality scores.

3.3.1: Design Activity Coding

To understand the design process, we synthesized a prescriptive model of how design is accomplished from several engineering design texts [18]. As detailed in Table 1, this model consists of three design stages that are further broken down into eight design activities. The design activity definitions were then used to code the transcripts of the verbal protocol data. Before coding began, however, the transcript was segmented into idea units. Each segment was then timestamped with a start and end time derived from the audio or video recording. Taking the segmented transcript, two trained researchers independently assigned a design activity to each segment. Once finished, the two compared results and arbitrated any discrepancies to agreement. For each transcript, a minimum level of intercoder reliability was required in order to ensure replicability.

The result of this entire process is a breakdown of a participant's design session into a series of different design activities (and thereby stages). The timestamps on the segments also allows for quantification of when and how much time was spent in the different activities and stages.

Table 1. Definitions for design activities and stages. Code abbreviations are in parentheses.

DESIGN STAGES	
Stage	**Activities Involved**
Problem Scoping (PS)	Problem Definition, Gathering Information
Designing Alternative Solutions (DAS)	Generating Ideas, Modeling, Feasibility Analysis, Evaluation
Project Realization (PR)	Decision, Communication
DESIGN ACTIVITIES	
Activity	**Definition**
Problem Definition (PD)	Defining the details of the problem
Gathering Information (GATH)	Collecting information needed to solve the problem
Generating Ideas (GEN)	Thinking up potential solutions (or partial solutions)
Modeling (MOD)	Detailing how to build a solution or parts of a solution
Feasibility Analysis (FEAS)	Assessing possible or planned solutions (or partial solutions)
Evaluation (EVAL)	Comparing two or more solutions within constraints
Decision (DEC)	Selecting one idea or solution
Communication (COM)	Revealing and explaining design elements to others

3.3.2: Quality Scoring

In both design studies, the playground design proposed by each participant was assessed for quality [3, 17]. Based on criteria from a guide to playground design, the quality score measured multiple aspects of the design, including: fulfillment of problem constraints; diversity of activities; aesthetics; protection from injury; uniqueness; and technical feasibility. The quality of individual components of the playground, such as slides or sandboxes, was also assessed if included by the participant. In both studies, methodological care was taken to ensure the reliability of the quality scoring as well to ensure compatibility between the student and expert studies. With 1.0 being the highest possible quality score, the actual scores by participant group were as follows: freshmen: range 0.19-0.63 (avg. 0.45); seniors: range 0.29-0.70 (avg. 0.51); and experts: 0.43-0.67 (avg. 0.54). In this paper, we do not report actual quality scores and instead report a participant's design as having scored low, medium (average), or high within their cohort group. This decision is so the reader can focus on the representations and avoid having to interpret an abstract quantification.

3.4 Findings

These studies provided many findings about how practice and education influence the engineering design process. Some findings were as expected: seniors tended to have higher quality designs than freshmen. Interestingly, the quality scores between experts and seniors were not significantly different, although we do note that the expected trend of quality increasing with experience was still present.

We also found that as designers gain more experience, they ask for more information of a broader scope such as maintenance and safety issues. Experts spent significantly more time in *problem definition* than seniors. Experts also spent significantly more time in the *gathering information* activity than seniors. Additionally, the experts gathered significantly more information that covered significantly more categories than the students [3, 17].

Our comparisons of freshmen and senior design processes [3] found that while the seniors spent more time in the *project realization* stage (which encompasses both the *decision* and the *communication* activities) than the freshmen, neither group spent very much time in this stage. Experts spent more time than seniors in *project realization* overall as well as in the decision activity itself.

One more finding is that a designer's understanding of a problem or possible solutions evolves through a process of iteration. Adams (2001) analyzed iterative activity in engineering design across levels of performance and experience [12]. Observations from the coded data provide windows into how designers continually revisit and reflect on each aspect of a design task. One of Adams's most interesting findings is that seniors not only spend more time iterating, but also spend more time engaged in "coupled" iterations in which the *problem definition* and solution co-evolve.

4 PROCESS REPRESENTATIONS

The statistical findings above provide only part of the picture about the design process. To really understand how the process adjusts, shifts, and adapts as it progresses, we have found it necessary to provide a lens into what our participants were actually doing and when they were doing it. As such, we have developed and refined three different representations showing the interplay between design activities and stages across the design process. In this section, we provide examples of each representation: timelines, cumulative time plots, and process time plots, and describe them in detail.

4.1 Timelines

The representation we call a timeline is actually a collection of individual timelines arranged together. As shown in Figure 1, each code (design activity or stage) is given its own horizontal space, and time is represented from left to right. For each segment of the transcript, a mark is placed on the line corresponding to how the segment was coded and at the appropriate location given the segment's start time. The width of the mark is proportional to the duration of the segment.

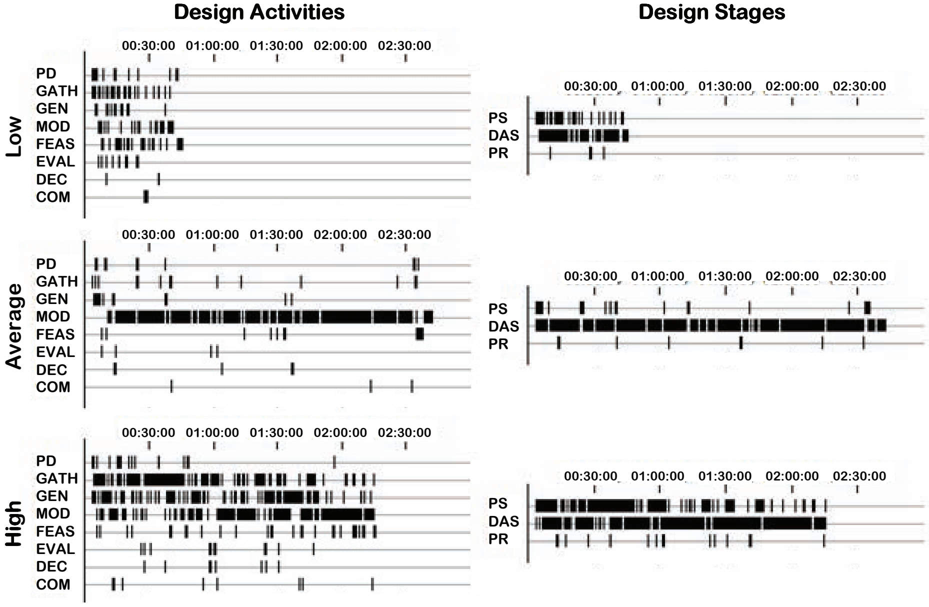

Figure 1. Design activity and stage timelines for low, average, and high performing freshmen engineering students. The timelines on the left were originally published in [17].

A timeline shows not only when and for how long a participant worked in the different design activities and stages, but it also reveals how the emphasis on different activities and stages shifts throughout the course of the design process. For example, consider the design activity timeline for the average-performing freshman in Figure 1 (2nd row, 1st column). We see that the participant initially engaged in *problem definition*, gathered a little information, came up with an idea or two, did a great deal of *modeling*, and briefly resumed defining the problem near the end of the design process. The design stage timeline (2nd row, 2nd column in Figure 1) reveals a similar pattern. The participant engaged mainly in *designing alternative solutions* while engaging in *problem scoping* primarily within the first 30 minutes and again for a brief period near the end of the process. Interestingly, this participant performed *project realization* on a regular frequency throughout the design task.

Timelines also represent the rate at which a designer transitions between different activities and stages. A low transition rate means multiple, consecutive segments are coded with the same code and correspond to a solid block on the timeline. The design activity timeline for the average-performing freshman in Figure 1 (2nd row, 1st column) shows such an example with *modeling*. A high transition rate area consists of consecutive segments shown as small, thin marks for two or more codes. High transition rates are seen throughout the design activity timeline for the low-performing freshman (1st row, 1st column in Figure 1) and in many parts of the high-performing freshman's design activity timeline (3rd row, 1st column in Figure 1). Note that design stage timelines tend to not show high transition rate areas as readily due to there being fewer codes. Areas with high transition rates between stages indicate periods of shifting emphasis in the participant's process.

The reader might note a similarity between our process timelines and the Gantt chart. The Gantt chart is a specialized bar chart used to illustrate a project schedule [19]. As in our timelines, time is represented on the horizontal axis. The vertical axis lists different tasks and subprojects, and blocks on the graph indicate when these tasks should be started and completed. Hence the primary difference between a Gantt chart and our process timelines is that the Gantt chart prescriptively describes how time should be allocated on a project or problem, while a timeline represents the actual allocation of time on tasks during the completion of a project.

Overall, the timeline is a rich representation for understanding the design process. Its primary strength lies in its separate visualization of each code that allows for clear analysis of each code's behavior but also readily allows for comparisons across the different codes. Additionally, a timeline is easily scaled to include any number of codes; we have used upwards of 19 codes in our timelines [20].

Drawbacks and weaknesses do exist for the timelines, however. The order in which the codes are listed on the vertical axis does influence the visual interaction among the codes. We choose to list the design activities in the order they appear in our model of the engineering design process, partially because we are more interested in how conceptually-similar tasks (e.g., *modeling* and *feasibility analysis*) interact rather than more separate activities (e.g., *gathering information* and *communication*). Another weakness of the timelines is the issue of *resolution*. The timelines in Figure 1 show a time span of three hours in a space 390 pixels wide, meaning that each pixel represents approximately 27.7 seconds. The average durations for segments in the three transcripts represented in Figure 1 are 7.9, 21.8, and 3.9 seconds, respectively. Thus, a single pixel might represent multiple segments, meaning that gaps could be lost. This resolution issue also explains why despite the segments being disjointed in time from each other, some of the codes appear to overlap in time. These resolution effects can be reduced by rendering the timelines at a larger scale or by adjusting the timescale to more efficiently use the space. For example, the low-performing freshman's timelines would be more clearly rendered if the timescale only went up to 1 hour. Unfortunately, for comparing multiple participants' timelines, they all need to be rendered at the same timescale to avoid distortions. Thus, all timelines to be compared will be rendered for the maximum time spent by any participant.

4.2 Cumulative Time Plots

The cumulative time plot (CTP) is a very different representation than the timeline and is similar to the cumulative time charts presented by Chimka and Atman [15]. As shown in Figure 2 (and in greater detail in Figure 3), a cumulative time plot is a traditional x-y line plot where each code is represented as a separate curve. The x-axis represents the duration of time working on the problem. Note that time is normalized as a percentage of total time spent. If a participant spent three hours on the playground task, then 25% represents the 45 minute mark, while for a participant who only worked for one hour, the 25% instead represents the 15 minute mark. The y-axis also represents time, although it is the total time accumulated by the participant. Each curve in a CTP thus represents the amount of time a participant spent in each code thus far in the process. For example, the design activity CTP for the average-performing freshman in Figure 2 (2nd row, 1st column) reveals that after working for 37% of their total time, the participant had engaged in 40 minutes of *modeling*. The same participant would go on to engage in 80 additional minutes of *modeling* in the remaining 63% of time used.

Cumulative time plots directly demonstrate the relative emphases a participant places on the different codes and how those emphases change over the course of the design process. Looking at the curves at the 100% mark in the high-performing freshman's design stage CTP in Figure 2 (3rd row, 2nd column), we see that the participant spent about 2.5 times as much time overall in the *designing alternative solutions* stage as in the *problem scoping* stage. However, up until about the 37% mark, the participant was spending roughly equal time in both stages.

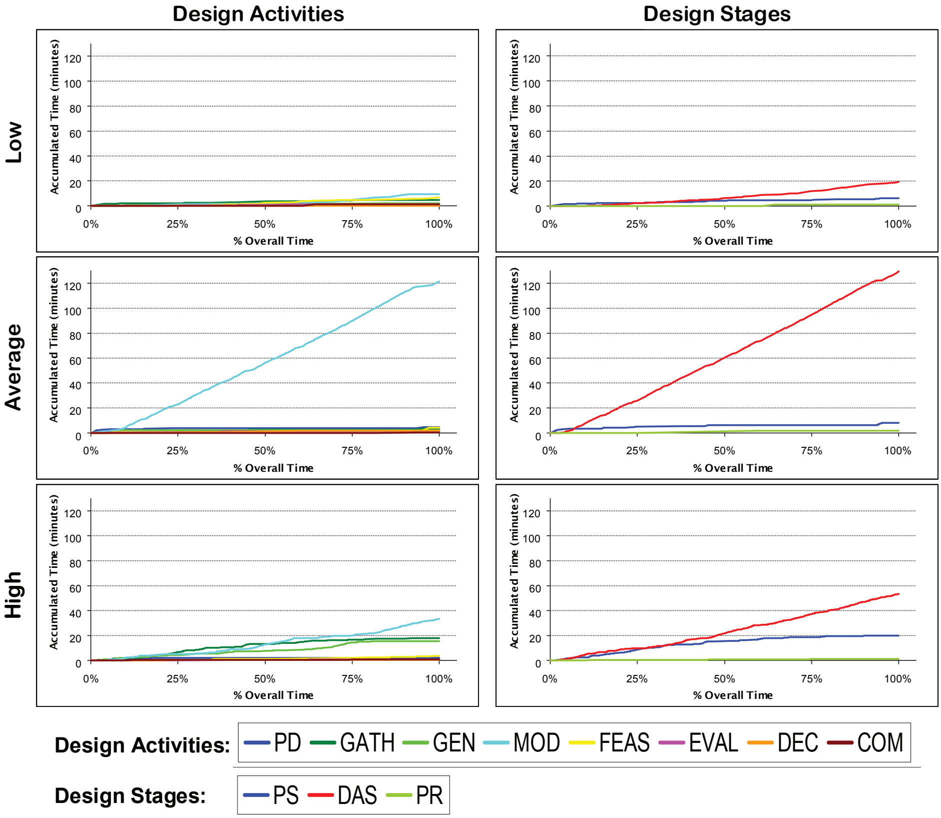

Figure 2. Cumulative time plots of design activities and stages for low, average, and high performing freshmen engineering students. See Table 1 for code abbreviations.

The changing slopes of the curves in a CTP also provide insight into the participant's design process.

As stated previously, most segments in the transcripts are short in duration, rarely lasting beyond a minute or two. Thus, a single segment does not add much to a code's running total, but when multiple, consecutive segments share the same code, the accumulated time will noticeably rise. Such a region will have a strongly positive slope. In the average-performing freshman design activity CTP in Figure 2 (2nd row, 2nd column), the sharp rise in modeling after the 10% mark is one such region. Notice as well that the *modeling* slope drops at the 90% mark. This region corresponds to the brief period of *problem scoping* at the end of the average-performing freshman's timelines in Figure 1.

Slopes also indicate when the participant finished engaging in a specific design activity or stage. This occurs at the point where a curve's slope hits zero and the curve becomes a horizontal line. In the cumulative time plots in Figure 3, several of these points are noticeable. The participant finishes *modeling* at about the 90% mark. *Project realization*, surprisingly, ends around the 60% mark.

The above discussion of slopes demonstrates one of the strengths of the CTP representation—it provides a direct quantification of the time spent in the different design activities and stages while maintaining the notion of an underlying process taking place. The changing slopes also provide insight into how the participant shifted her focus among the different design tasks.

A second strength of the CTP is how it more readily allows for comparisons across participants due to its use of a normalized time scale on the x-axis. As discussed in the previous section with timelines, the different time spent by participants on the playground design problem effects the timeline representations. Normalizing the time removes this effect in the CTPs. Moreover, in the original Atman et al. study, total time spent solving the playground task was found to be only a moderate correlate of the quality score, with several other measures showing stronger correlations to quality score [17]. Spending more time does not automatically equate to a better design or underlying design process. Thus, the fact that the CTP does not represent total time on task does not impact its usefulness in a major way. The cumulative time plot allows one to find two participants with similar design processes despite one having spent 30 minutes more on the problem.

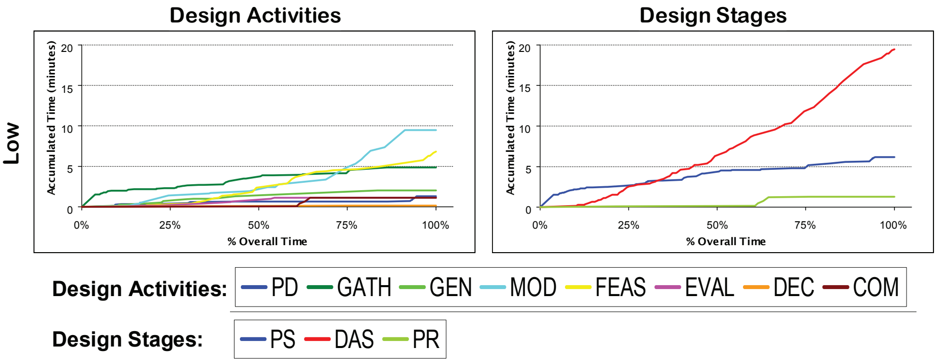

Figure 3. The low-performing freshman engineering student's cumulative time plots from Figure 2 with an adjusted y-axis. See Table 1 for code abbreviations.

The CTP does come with notable weaknesses, however. One of the most noticeable faults of the representation is seen in how much easier it is to interpret the design stage CTPs than the design activity CTPs. More codes to plot mean a greater chance of overlap and difficulty in distinguishing the different curves. Even with a small number of codes, some codes may still overlap if they accumulate time at a similar rate. Note how *gathering information* and *generating ideas* grow at a similar rate throughout the design activity CTP for the high-performing freshman in Figure 2 (3rd row, 1st column). Extreme differences in the accumulated times also present difficulties for the cumulative time plots. In our studies, some of our participants heavily emphasized certain design activities over the others. The average-performing freshman CTPs in Figure 2 (2nd row) is a common example. This participant spends two orders of magnitude more time in modeling and design alternative solutions than the other design activities and stages, and this vast difference obscures the details of the underused codes. Although adjusting the y-axis to a log-scale would reduce the disparity, we would still have the problem of the seven other activity codes overlapping.

A final weakness of the CTP occurs when comparing multiple participants' CTPs. As already discussed, the normalization of the x-axis makes comparisons easier, but the accumulated times on the y-axis are proportional to the total time spent on task. This is most notable with the low-performing freshman in Figure 2 (1st row). Having spent only 46 minutes total on the playground problem, it is of no surprise that the accumulated times never exceed 20 minutes. However, to compare this freshman with the other two requires using the same y-axis bounds. Thus, little detail is seen in the CTPs for the low-performing freshman in Figure 2. In Figure 3, however, more appropriate bounds on the y-axis reveals far more details. In fact, the shapes of the low-performing freshman's CTP in Figure 3 bears several similarities to the shapes of the high-performing freshman's CTPs in Figure 2 (3rd row). One can conjecture that had the student spent more time overall, the low-performing freshman could have produced a design of much higher quality.

4.3 Progress Time Plots

The progress time plot (PTP) is a variation on the cumulative time plot, and addresses some of the CTP's weaknesses. This plot is similar to a plot used by Gero and McNeill [8]. The basic idea is to normalize the y-axis similarly to how we normalized the x-axis in the CTP. Instead of showing the accumulated time per activity or stage, the y-axis now shows what percentage of an activity or stage has been completed. Otherwise, the PTP uses the same x-axis as the CTP and also contains a separate curve for each code. Figure 4 shows the activity and stage PTPs for our three example freshmen. Interpreting a PTP is similar to interpreting a CTP. Consider the design stage PTP for the high-performing freshman in Figure 4 (3rd row, 2nd column) and its equivalent CTP in Figure 4. At the 50% point throughout the total time, the CTP says that the participant has spent about 16 minutes thus far in *problem scoping* and will eventually spend a total of 20 minutes in *problem scoping* overall. At this point, the participant has completed 80% (16 divided by 20) of the *problem scoping*, so the PTP shows the curve for *problem scoping* at 80% at overall time 50%. One additional difference with the PTP is that the curves are drawn as step functions and not as linear curves as with the CTP. In a CTP, a single segment does not dramatically increase the accumulated time for that code. However, in a PTP, a single segment can result in a dramatic increase in completion for a code. This is seen strongly in Figure 4 with the curves *decision*, *communication*, and *project realization*. These stage and activity codes are rarely performed by the freshman participants (see timelines in Figure 1 for confirmation), meaning that a 20 second segment can account for 40% of overall time for these codes.

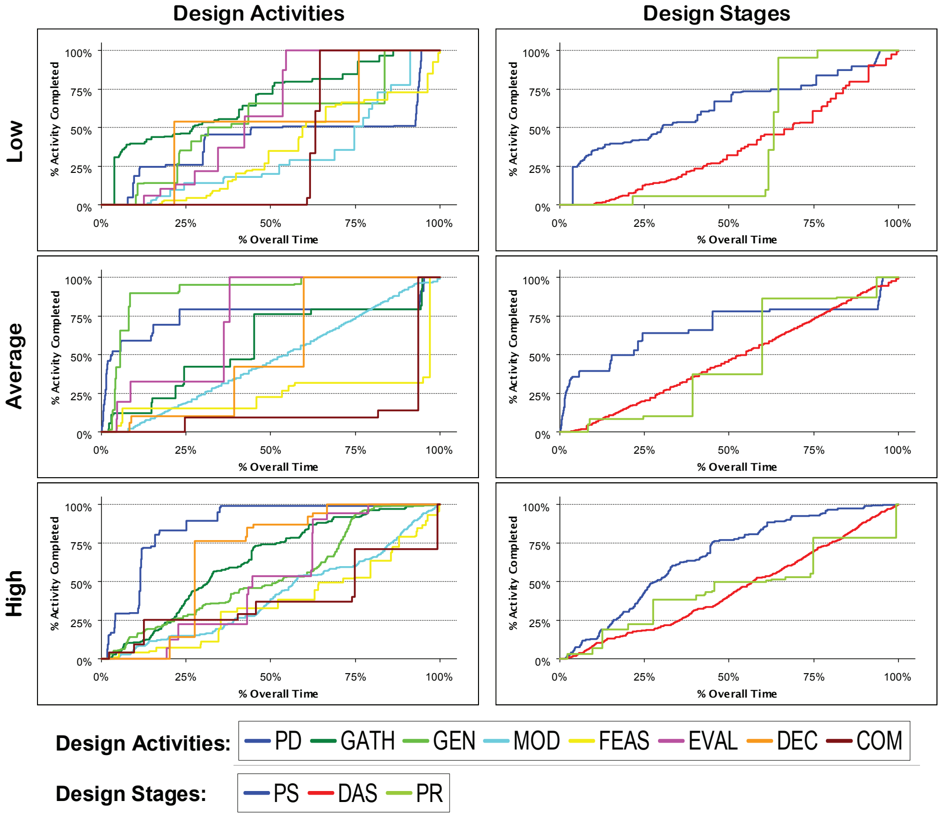

Figure 4. Progress time plots of design activities and stages for low, average, and high performing freshmen engineering students. See Table 1 for code abbreviations.

As with timelines and CTPs, progress time plots also reveal how the participant transitions between the activities and stages. Consecutive segments with the same code will result in small jumps along the x-axis. Wider plateaus where the y-value of a curve does not change indicate times when the code is not used. A good example of these two phenomena can be seen in the low-performing freshman's design stage PTPs in Figure 4 (1st row, 2nd column). Prior to the 63% overall time mark, project *realization* segments occur infrequently. At that point, though, four *project realization* segments occur in near succession. Afterwards, it is not until the 75% overall time mark that another *project realization* segment occurs, hence the plateau in the curve from the 65% to 75% marks.

The progress time plot is particularly useful for characterizing a participant's design process as it is easy to identify when a person starts, is halfway through, and finishes with a design activity or stage. For example, the design activity PTP for the high-performing freshman (Figure 4, 3rd row, 1st column) shows that the participant began defining the problem (PD) very early on, had completed 50% of the *problem definition* work in the first 13% of time spent on the problem, and was finished with *problem definition* around the 35% mark. The low-performing freshman's PTP (Figure 4, 1st row, 1st column), however, reveals a much different profile. This participant begins *problem definition* around the 8% mark, and only completed half of the work in defining the problem at the 50% mark, and completes *problem definition* at the 90% mark.

This is another strength of the PTP—the ability to directly compare the design processes of different participants. Because both axes are normalized, one can directly compare the shapes of the curves without needing to adjust for time spent on task. Once a pattern is identified, it can be described quantitatively. Detection of the pattern could then potentially be automated.

The PTP also avoids some of the other weaknesses of the CTP. Because of the step functions, the plots suffer from less overlap. Compared to the design activity CTPs (Figure 2, 1st column), it is far easier to identify the different curves in the design activity PTPs (Figure 4, 1st column). The PTP is also not affected by the participant overwhelmingly emphasizing one activity over another since the y-axis is normalized. These benefits do not come freely, however. The progress time plot completely hides any notion of scale in the data. A PTP cannot show that one person spent more time on the problem nor show the relative amounts of time spent in the different activities and stages. Everything is equalized.

4.4 Summary of Representations

The three representations—timelines, cumulative time plots, and progress time plots—all utilize the same source of data. Timestamped, segmented transcripts are coded according to a model of the engineering design process. The representations refine this data into visually intriguing descriptions of how an engineer adjusts her approach depending on when and where she is in the design process.

Despite sharing the same underlying data source, the representations are different and highlight different aspects at the cost of ignoring others. None of the three are superior to the others, however, for each has its own strengths and weaknesses. The timelines are rich and detailed, clearly separating each activity and stage. However, providing a quantitative insight about when one activity or stage dominates another is less precise. Cumulative time plots make clear the relative, quantitative differences in the shifting emphases among activities and stages throughout the design process. These plots, however, can also be difficult to read due to overlaps, crowding, and issues of magnitude. The progress time plots make clear when stages and activities are emphasized or ignored and makes comparing individuals a straightforward and direct task. However, senses of scale and magnitude are completely lost. To truly understand the complexities of how engineers do design, all three representations are valuable tools for generating insights, each supporting the others' weaknesses.

5 APPLICATIONS OF THE REPRESENTATIONS

The three representations have found multiple uses throughout our research and in additional arenas. In this section, we discuss a variety of both our past and ongoing applications of the representations.

5.1 Generating the Representations

Before one can utilize the representations, one needs to generate them from the data. Ideally, generating the representations should be relatively easy and efficient. Moreover, little should be required to prepare the data for visualization. In our work, the segmented, timestamped transcripts of the verbal protocol data are stored in a spreadsheet format. As such, we utilize the built-in charting functions in Microsoft® Excel to generate the cumulative and progress time plots. We have also programmed an Excel template to automate the generation of these time plots. One now has to simply copy and paste in the timestamp data and design codes for each segment, and the plots will be generated in a few seconds. Generating the timelines, however, has proven to be a more complex matter and not readily accomplished as an Excel chart, therefore we have developed our own software to produce the timelines. Through repeated use in our studies and research, both the Excel templates and the timeline software have gone through multiple iterations of debugging and refinement. Thus, we plan to make these tools available for use by anyone (please contact the authors).

5.2 Applications in Research

Although we have used these representations in multiples areas of our research, one of their most powerful uses has been in providing insight into our massive amount of verbal protocol data. On multiple occasions, we have taken all of the timelines, CTPs, or PTPs for all of the freshmen, seniors, and experts and literally covered a wall or table with all of the representations arranged by their cohort groups or quality scores. We then engage in the natural human behavior of pattern-seeking. Do the experts show a different *problem scoping* process from the freshmen? Do those with higher quality scores show more *feasibility analysis*? Any insight, question, or pattern we see among the field of representations can then become an impetus for further exploration.

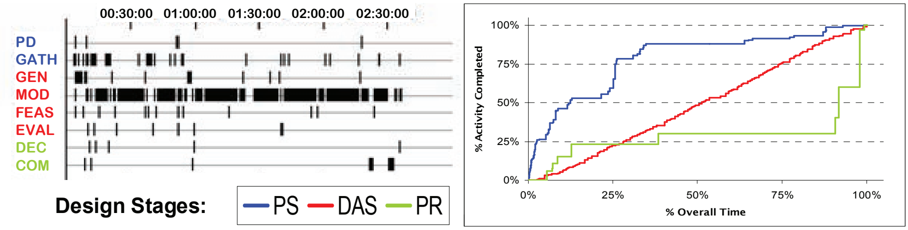

Figure 5. Example of a cascade design process as seen in a senior's design activity timeline and design stage progress time plot. See Table 1 for code abbreviations.

One insight of note was that the design activity timelines for many of the engineering experts featured a familiar pattern. This pattern was also seen among several of the seniors but very rarely among the freshmen. This pattern can be described as a *cascade* through the design activities over the time spent designing. A significant portion of time at the start of the design process is spent in *problem scoping* which gradually shifts into a more concentrated focus on *developing alternative solutions*. Some transitions back into *problem scoping* occur throughout the process as well as transitions into *project realization*. An example of a cascade pattern from a senior is shown in Figure 5.

Once the cascade pattern was found and a definition was established, two researchers independently labeled each timeline as being either a cascade or not and then arbitrated to consensus any disagreements [3, 21]. This labeling revealed that the cascade pattern was in fact very common among the experts (14/19), less common among the seniors (9/24), and rare among the freshmen (4/26).

Although the design activity timelines initially helped identify the cascade pattern, the design stage PTPs have proven quite useful for refining the definition of a cascade. Like the design activity timelines, the design stage PTPs of cascades show a similar pattern as shown in Figure 5. A fairly smooth curve of *designing alternative solutions* is bounded above by a curve of problem scoping and below by a curve of *project realization*. Moreover, the *problem scoping* curve rises quickly early in the design session and then slows dramatically. In a reverse fashion, the *project realization* curve shows slow progress until late in the session. Current research is under way to use the design stage PTPs of cascades to quantitatively define the pattern already found qualitatively.

Another hypothesis under current investigation comes from a similar pattern observation about the design activity cumulative time plots. As can be seen in the CTPs in Figures 2 and 3, *modeling* eventually becomes the dominant activity in the processes of all three freshmen. With nearly every participant, modeling eventually dominates the other activities in terms of accumulated time. When this dominance occurs, it appears to be linked to both experience and the quality of design. *Modeling* appears to come to dominance early in the process for freshmen but increasingly later for seniors and experts. Higher quality designs appear to have *modeling* dominating later as well, but perhaps delaying emphasizing *modeling* until too late in the process is detrimental? These and other questions inspired by the representations are currently under study.

5.3 Applications in Education

Another exciting usage of the representations has been our recent work in bringing our research findings into the classroom. Our team has collaborated with engineering instructors in capstone design and other project-based courses to improve their students' awareness of the components, complexities, and benefits of well-planned and well-executed engineering design processes. We have developed interactive seminars where students analyzed the design process timelines, discussed insights with their peers, and reflected on their own design processes [22].

Students in one class exercise, for example, were asked to examine a set of freshmen and senior design activity timelines and tell us what they found. They were able to identify and describe in their own words several of the important findings from our research. As one student posited, "Problem definition is key to the overall project. Remind yourself of what you are doing and what is really being asked. Pick your head up from the paper (modeling!) and analyze the problem." Another student stated, "Realization of how the design process moves from one portion to the other was the best aspect of this talk. I didn't realize how important the reiteration of certain aspects of the process [are]." The students were readily able to interpret the timelines and make important insights.

We are continuing to explore the usage of our timelines and other representations in classroom settings. One goal is to eventually make our collected data and their representations available to all engineering instructors along with instructions for suggested classroom activities. Another goal is to develop tools to allow students to record their own design processes for eventual visualization.

5.4 Applications in Outreach

Representations have also provided a useful tool for communicating with people outside the engineering design research community. When presenting our work to colleagues, industry leaders, and many others, we have found that with only a few minutes of explanation, our audience understands the representations. They then readily engage in insight and conjecture about the design process and easily see our other research findings within them. This is perhaps the ultimate test of any data visualization—making complex data accessible to any viewer.

6 CONCLUSIONS

Representations are powerful tools for researchers, providing insights into the data. For us, the timelines, cumulative time plots, and progress time plots have been invaluable in our studies of the engineering design process. Not only will we continue to use these representations, we encourage and plan to support others in their usage.

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