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INSIGHTS ON DESIGNERS' SKETCHING ACTIVITIES IN NEW PRODUCT DESIGN TEAMS

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ABSTRACT

This paper describes an empirical study of student designers' sketching activities in new product design teams. A comprehensive list of metrics associated with sketches is identified and their relative level of importance at different stages in the design process is evaluated. Correlations between sketching activities, variety of the concept sketches, and design outcomes are presented. Results show the volume of total sketches and the number of 3-dimensional sketches has an increasingly positive effect on the design outcome as the design proceeds from preliminary investigation, through conceptual design, to detailed development and testing. Results also show that there is a statistically significant correlation between the total number of individual journal sketches created during the design process and an individual student's class grade.

Keywords: sketches, drawings, design process, concept generation, design journals, design teams.

INTRODUCTION

In all engineering design domains – from software to hardware, from architecture design to mechanical design – graphical communication plays a key role throughout the design process, especially during the conceptual, formative phases. We identify a comprehensive list of metrics associated with sketches and drawings and evaluate their relative level of importance in the design process and their correlations with successful design outcomes.

In this paper, we use the word "sketch" quite broadly to include all early stage forms of graphical representations of a design, including rough freehand or computer-rendered drawings and conceptual solid models. A design sketch represents the chief features of an object or scene and is often made as a preliminary study of a design concept. In creating the sketch, the designer is involved in a process of attempting to give external definition to an imagined, or only half imagined, suggestion for a design form [1]. Design sketches can be informal in character, and usually fall short of precisely determining positions and dimensions; they are the kind of representation that will allow the designer to "try out" a new idea on paper, quickly and cheaply. While sketching can be rapid and spontaneous, its residual traces are stable and can be subsequently examined by the designer at a later time.

Sketching, being an integral part of the design process, can be used to store the design solutions, highlight conflicts and possibilities [2] as well as form the basis for revising and refining ideas, generating concepts and facilitating problem solving [3]. Therefore, sketching can have a positive impact on the quality of the designed solution and on the individual experience of the design process [4]. Serving as an aid for analysis, short-term memory, communication and documentation [5], sketching can facilitate and hasten the development of ideas and concepts into a successful product.

Since sketching is important in the process of engineering design, understanding and analyzing sketching activities are ongoing research topics within the design community. Much effort has been placed on evaluating their impact on the individual designer [1-8]. Fewer studies cover the use of sketches in group settings.

In this paper, we analyze the sketching activities of new product design teams during a semester long undergraduate class at UC Berkeley. This test bed was composed of thirteen design teams that varied in size from three to seven members. Two additional teams were not included in this study as their design documentation was incomplete.

We address four research issues. First, what are useful metrics for characterizing design sketches? Second, how do sketching activities evolve over time? Third, are sketches indicative of the design space explored? And finally, are there any correlations between sketching activities and the outcome of the team? That is, what insights into the design process and individual experience will analyzing sketching activities provide?

RELATED WORK

There is a considerable body of research in sketching activities in both the design theory literature as well as in literature in cognitive psychology and cognitive science [9-11]. Purcell and Gero [12] provide an extensive summary of this prior work.

One characteristic of the design process in all areas of design is the use of a number of different types of drawings – with a single type being predominant in each stage of the design process. Goel concludes from his experiments that designers tend to use the relatively unstructured and ambiguous sketch early in the process, but structured precise representations as the design document gets closer to delivery to the customer [13].

In an engineering context, Ferguson [14] identifies three kinds of sketches: *thinking* sketches, *prescriptive* sketches, and *talking* sketches which are used to focus and guide non-verbal thinking, to help develop the finished drawing, and to communicate and exchange ideas during discussion, respectively.

Ullman considers three other features of engineering drawings [5]:

- *Type of marks-on-paper*: support notation and graphic representations. Support notation includes textual notes, lists, dimensions, and calculations. Graphic representations include drawings of objects and their functions, and plots and charts
- *Medium to produce drawings*: traditional versus digital media
- *Type of graphic representation*: 2D drawing versus 3D drawing
- *Level of abstraction* of the information to be represented: from abstract concept to a final, detailed, drafted design.

Ullman's last feature – *the level of abstraction* – is similar to the complexity measure defined by McGown et al. [6]. In our research, we exploit five different levels of complexity as described in the "methodology" section.

Goel conducted one of the most detailed studies of the act of sketching [13]. He identifies two types of operations occurring between successive sketches in the problem-solving phases: *lateral transformations* and *vertical transformations*. In a lateral transformation, movement is from one idea to a slightly different idea. In a vertical transformation, movement is from one idea to a more detailed and exact version of the same idea.

In a detailed case study of engineering design, Yang examined the timing of types of sketches as one of the factors in the design process that contributes to a design's success or failure [15]. Yang's study suggested that there is a statistically significant correlation between the quantity of early, dimensioned drawings and the graded design outcome.

Shah et al. [16] defined "*variety"* as a measure of the explored solution space during the idea generation process. They examine how each function is satisfied with a collection of concepts and apply a variety rating to an entire group of similar ideas, not an individual idea. Ideas are grouped based on how different two ideas are from each other. The use of a different physical principle to satisfy the same function makes two ideas very different.

METHODS AND TEST BED

A project-based product design course in the Department of Mechanical Engineering at the University of California at Berkeley provided the test bed for this study. In this course, senior undergraduate student teams of four to seven students conceive, synthesize and prototype engineered products. They work together as a unit in self-selected and self-managed teams, with feedback from the instructor, teaching assistants and industry coaches. The design process proceeds from ideation to concept generation, detailed design, financial analysis, and the development of a working prototype in a four-month semester period. There were two primary sources of design data used in our study: (1) paper-based design journals kept individually by the students throughout the term and (2) team deliverables submitted at each stage gate of the design process. The journal captured students' ideas, thoughts, and reflections about their designed artifact, group dynamics, and the design process itself through words and sketches. Team deliverables include mission statements, customer feedback, concept sketches, product specification and drawings, prototypes, presentation materials, product testing, and team reflections on the design process and product.

Our research analyzed the sketching activities of 57 senior mechanical engineering students as they worked on the design of 13 different products extending over a four month semester period. In addition to the 57 design journals from each student, there were 459 team documents analyzed, including 260 conceptual design sketches. In light of the continuum of graphical representations used in engineering design, we studied all the drawings in the students' design journals and group documents, including free hand sketches, CAD drawings, photos, and drawings in other digital formats.

Both individual drawings in each journal and drawings in group documents were date stamped and characterized by metrics defined as follow:

- ***Generation****:* how the drawing was generated, whether it was a new drawing representing a new idea or a transformation of a previous drawing (either lateral or vertical transformation).
- ***Type****:* thinking sketches, prescriptive sketches, or talking sketches.
- ***Medium****:* traditional freehand sketches or drawings in digital form (CAD drawings, photos, or others)
- ***Representation****:* 2D, 3D versus 2D multi-view drawings.
- ***Annotation****:* type of support notation including labels, lists, narratives, dimensions, and calculation
- ***Level of detail****:* five levels of detail based on the complexity measure by McGown [6] and Shah's genealogical idea categorization [16].
    1. A line drawing that shows the physical principles (underlying physical law that governs the product concept expressed by the sketch) and technology applied, but no details to suggest product form. May include labels. No other text based annotations are used nor are numerical dimensions.
    2. A sketch or drawing that shows the working principles (mechanisms used to satisfy functionality) of the concept, but no details to

suggest product form. Line thickness varies to give emphasis. May include brief annotation.

3. A sketch or drawing that shows product form. May use rough shadings. May be annotated to describe certain aspects of concepts.
4. A sketch or drawing that shows product form with annotation. Certain product features are illustrated in detail. Dimensions may appear.
5. 3D form or multi-view 2D drawings to show the entire product form. Dimensions appear and annotations are used to ask questions or provide explanations.

Sketches in students' individual design journals and group documents were characterized by the above metrics and indexed along two axes with different granularities in the design process: time (date, week, design stage) and level (individual team member, team). Studies on time variation of sketching activities in the design process were conducted based on both data sources.

We also analyzed the 260 conceptual design sketches submitted as team deliverables for design stage 2. These sketches are different "design" solutions for a single concept direction. We applied the *variety* measure to quantitatively score each design team to show the broadness of the design team in exploring the solution space. Shah recommends examining how each design function is satisfied in order to measure variety. "A variety rating applies to an entire group of ideas, not an individual idea. The conceptual origins of ideas are analyzed through a genealogical categorization based on how ideas fulfill each design function. The nodes in the tree carry the count of ideas in each category at each level. The number of branches in the tree gives an indication of the variety of ideas" [16]. The variety measure M takes the following form:

$$M = \sum_{j=1}^{m} f_j \sum_{k=1}^{4} s_k b_k / n \quad (1)$$

where b_k is the number of branches at level k in the genealogical categorization tree of the concepts represented by the sketches; S_k is the score for level k, suggested scores are 10, 6, 3, 1 for physical principles, working principles, embodiment (giving concrete product forms to abstract product concepts), and detail (extended representation of certain aspects of the product form), four levels in the categorization tree; n is the total number of sketches and m being the total number of functions; and f_j is a weight factor that accounts for the different importance of each function. Details can be found in Shah et al. [16].

To gain insights as to which sketching activities contributed to successful design outcomes, we correlated the number of sketches of different types at different design stages with the design outcomes. How to best quantitatively characterize the quality of design outcome – including both the artifact produced and the design process – is still an open research question in the design theory community. In this study, we use the students' individual and team project grade that the instructor assigned to each student and the team as an indicator of design outcome and students' performance. The grades were based on a review of the individual student and teams' performance throughout the process, the quality of the final prototype and input on the final design from a jury of industrial reviewers.

Multiple correlations were also used to determine the relationship of design outcome, as the criterion variable, with the quantity of one type of sketch and the variety score of design concepts, as the two predictor variables. The multiple-correlation coefficient R_{123}, as shown in Eq. (2)., gave an indication of the degree to which the predictors, taken together, actually predict, in this study, the team design outcomes.

$$R_{123} = \sqrt{\frac{r_{12}^2 + r_{13}^2 - 2r_{12}r_{13}r_{23}}{1 - r_{23}^2}} \quad (2)$$

where r_{12} is the correlation coefficient between project grades and the total number of one type of sketch captured in the design journals and group documents for each team; r_{13} is the correlation coefficient between project grades and variety scores; and the last correlation coefficient, r_{23} is between the total number of one type of sketch and variety scores.

As a preliminary study, we conducted an inter-rater reliability test of the sketches and drawings from the student journals, Two raters rated the same randomly selected student journal. The percentages of agreements were 100% for *type, medium, representation,* and *annotation*, 93% for *generation*, and 91% for *level of detail.*

RESULTS

The distribution of types of sketches and drawings are first summarized over three design stages: stage 1 (1/19/03 ~ 3/8/03), stage 2 (3/9/03 ~ 3/22/03), and stage 3 (3/23/03 ~ 5/10/03), defined as (1) preliminary investigation including mission statement and customer user needs analysis, (2) detailed investigation including concept generation and selection, and (3) development and testing, respectively.

Evolution of Sketching Over Time

Figure 1. illustrates the total number of sketches made by all design teams in the three design stages. We can see from the bar chart that the greatest number of sketches was generated during stage 2, the conceptual design stage, with the least amount produced in stage 1, the preliminary investigation. This supports Purcell and Gero's hypothesis that verbal activities instead of drawings are used in the initial stages of the design process in order to explore and understand the design problem

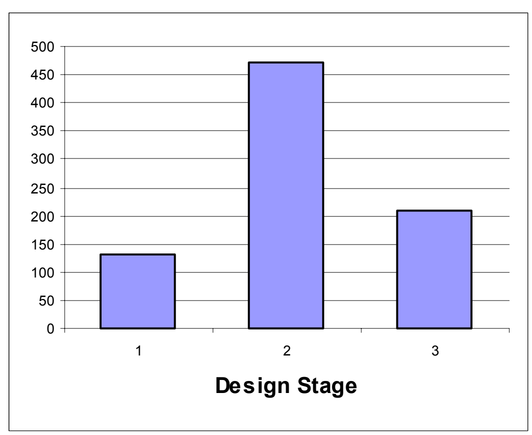


Figure 1. Total number of sketches by design stage.

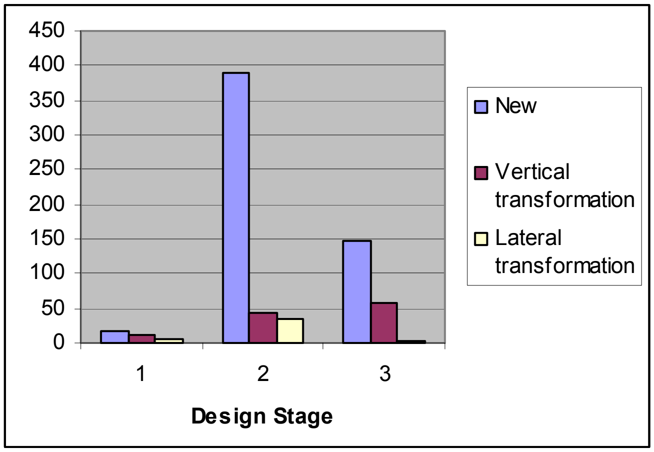


Figure 2: Generation of sketches by design stage**.**

[12]. It also supports the conjecture by Horst Rittel, an early researcher in the design sciences, that the early stages of the design process are inherently argumentative; the designer must continually raise questions and argues with her/himself and others over the advantages and disadvantages of alternative responses [17]. One might expect such "arguments" to be heavier in textual discussions than in graphical communications. Further detail on the association of different types of sketches with each design stage is shown in the following figures.

We observed that the majority of sketches were "new sketches" throughout the design life cycle with only a small portion being transformations of a previous sketch (Fig. 2.). This suggests that the design teams did try to explore the solution space by generating many new conceptual sketches. It is surprising that a large number of new sketches were still being generated in the last design stage. This could be explained by the fact that some of the teams faced challenging hurdles in the last stages that required substantial redesign. Others provided new sketches related to details of prototyping and assembly.

Thinking sketches were predominant throughout the design life cycle as demonstrated in Fig. 3. This was probably because most of the sketches came from the individual students' design journals, which were used to capture individual design thoughts

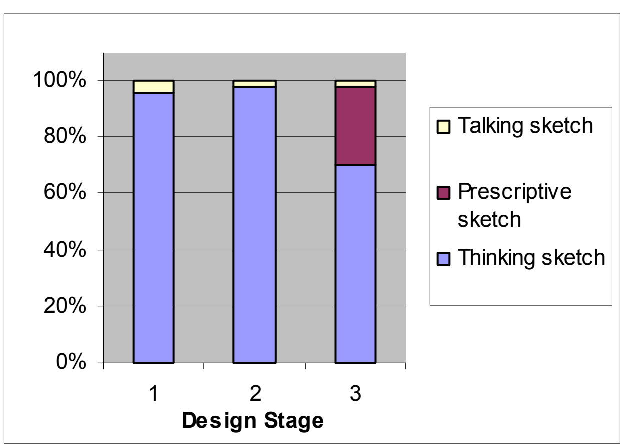


Figure 3: Type of sketches by design stage**.**

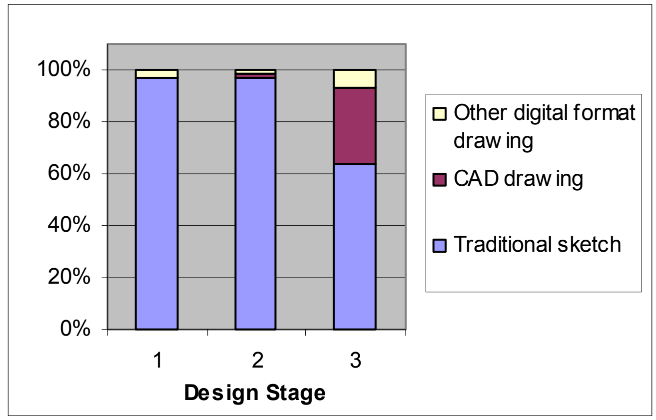


Figure 4: Medium of sketches by design stage.

and not group communication. We would expect to get more *talking sketches* if we had been able to capture the sketches produced during the teams' face-to-face meetings where sketches might be used as a tool to facilitate discussion. Another pattern in Fig. 3. is that nearly a third of the sketches in stage 3 are *prescriptive sketches*, which suggests that prototyping would follow.

We observed that CAD drawings emerged in the conceptual design stage 2 and greatly increased in design stage 3, where its proportion is almost 30 percent (see in Fig. 4.). As students could access the computer lab in the department freely, there were minimal differences in the availability of computer tools to individuals or groups in this study. Another pattern revealed was that most of the sketches were traditional freehand sketches. This supports Ullman's finding that a large percentage of an engineer's graphic representation is informal sketching [5].

As the design proceeded, students tended to sketch more in 3-dimensional space and less in 2-dimensional space as illustrated in Fig. 5. This could be explained by the fact that product design is a transformation process, designers need to transform an abstract concept into a concrete product. 3D representations or 2D multi-view sketches bear more product form information than 2D representations. To further interpret the use of 3D representations in different design stages, we studied the correlation between 3D representations and the design outcome. We will expand upon these results in the "correlation with design outcome" section.

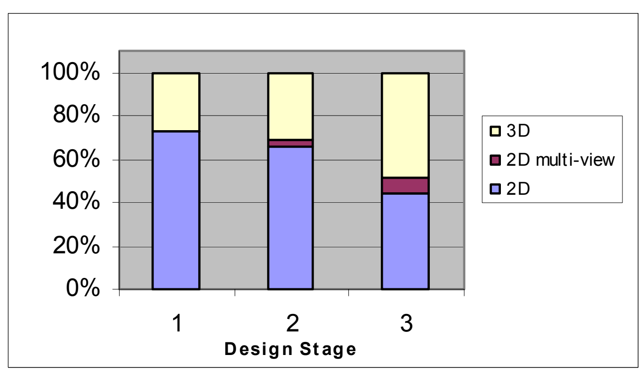


Figure 5: Representation of sketches by design stage.

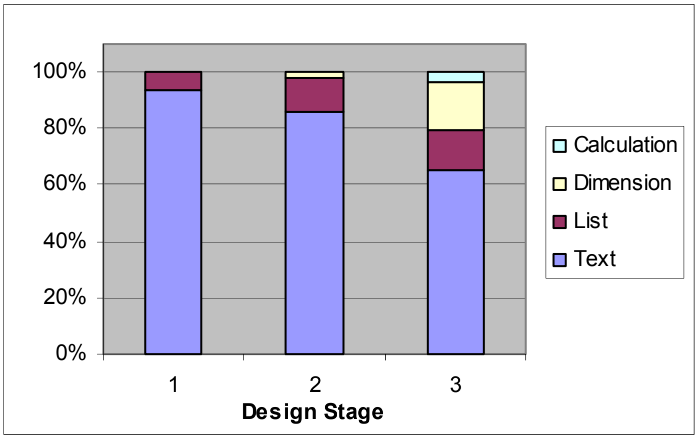


Figure 6: Annotation of sketches by design stage.

One notable trend identified in Fig. 6. was that *text* (labels and narratives), the dominant annotation type in the sketches, decreased over time, while the *list*, *dimension* and *calculation* type of annotation increased proportionately. Yang [15] found that the creation of more concrete dimensioned drawings early on in the design cycle has a positive effect on design outcome. Unfortunately, we didn't have enough dimensioned sketches early on in the design cycle to repeat Yang's experiment.

Three patterns emerged from the evaluation of the level of detail in the sketches (see Fig. 7.):

- The proportion of sketches with the lowest level of detail decreased as the design proceeded.
- The proportion of sketches with high levels of detail (level 4 and level 5) increased as the design proceeded with level 4 taking the largest proportion of sketches during the final design stage.
- Level 5 was at the highest in both proportion and absolute number in the final design stage.

It is clear that as the design progressed from the preliminary stage through refinement to detailed design, there was a marked increase in the level of detail and explicitness of the drawn material that was produced; that is, the drawings moved from unstructured sketches to more precise and explicit drawn representations. In addition to replicating Goel's findings [13] here, our research also supports Schutze's conclusion that early sketches with low level of detail were sufficient to support critical thinking and alternative generation. Because of the vague and undetailed representation, the designer has various open possibilities to change and improve her/his ideas [4]. Example sketches with different levels of detail are illustrated in Fig. 8.

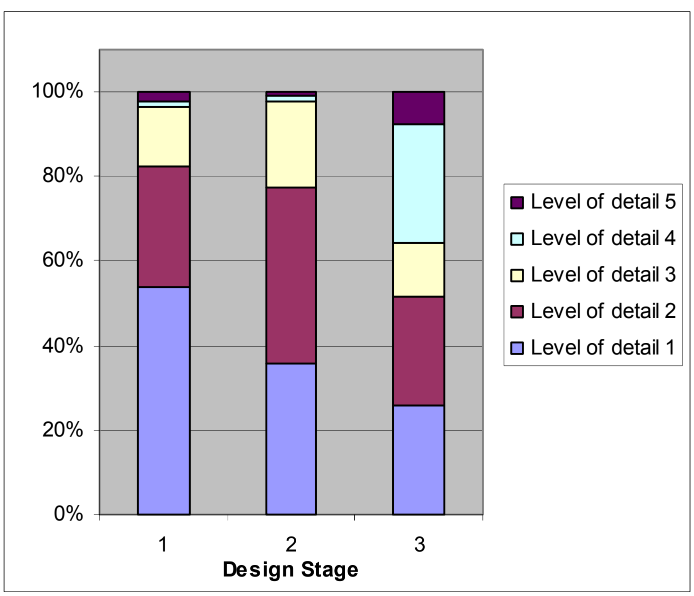


Figure 7: Level of detail of sketches by design stage.

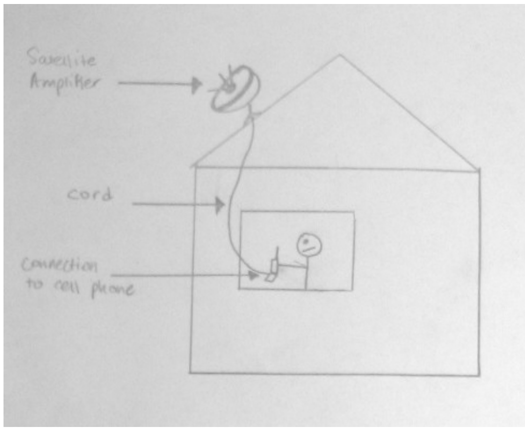
Exploration Of Solution Space

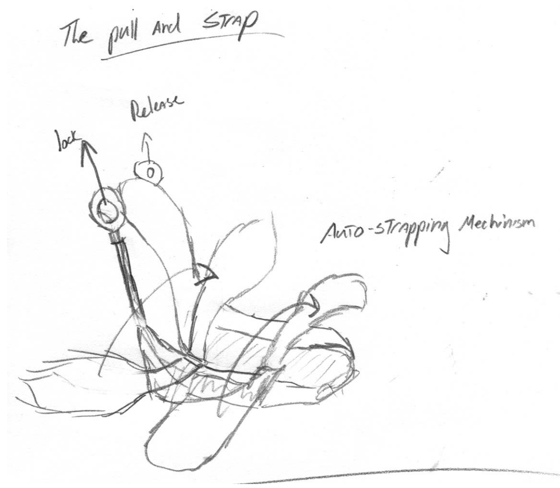
A product concept is an approximate description of the fundamental technology, working principles, and form of the product. The degree to which a product satisfies customers and can be successfully commercialized depends largely on the quality of the underlying concept. A good concept is sometimes poorly implemented in subsequent development phases, but a poor concept can rarely be manipulated to achieve commercial success. Good concept generation leaves the team with confidence that the space of alternatives has been explored fully. Thorough exploration of alternatives early in the product design process greatly reduces the likelihood that the team will stumble upon a superior concept late in the product design process or that a competitor will introduce a product with dramatically better performance than the product under development [18].

The quality of the product concept depends largely on how well the designers were able to explore the design space. To measure how each team, as a whole, explored the design space in our test bed, we applied Shah's *variety* measure to the conceptual sketches submitted by each team at the end of the second design stage. The measurement procedure was slightly modified to cover all cases in our study. Two raters constructed the classification tree and calculated the variety scores for all of the sketches in each team separately. The statistically significant correlations between these two raters are 0.76 for Pearson's correlation (degree of freedom df=11, significance level α=0.05, critical value R=0.476), and 0.62 for Spearman's rank correlation (population N=13, significance level α=0.05, critical value R=0.481). Average scores obtained using Eq. (1). from both raters are shown in Table 1.

The more the team explored the design solution space, the higher the *variety* score with a maximum value of 20 (all design alternatives are separated on the highest level of the genealogical categorization tree) and a minimum value of 0 (with only one concept generated). The midterm project grade was the grade that the instructor placed on the team with 10 as the maximum score. The midterm project evaluation occurred shortly after the second stage, the conceptual design stage. The final project ranking was the ordinal grade that the instructor placed on the team as discussed early in the "methods and test bed" section. A ranking of 1 signifies that the team was the best in the class. The last column reports the total number of sketches for each team.

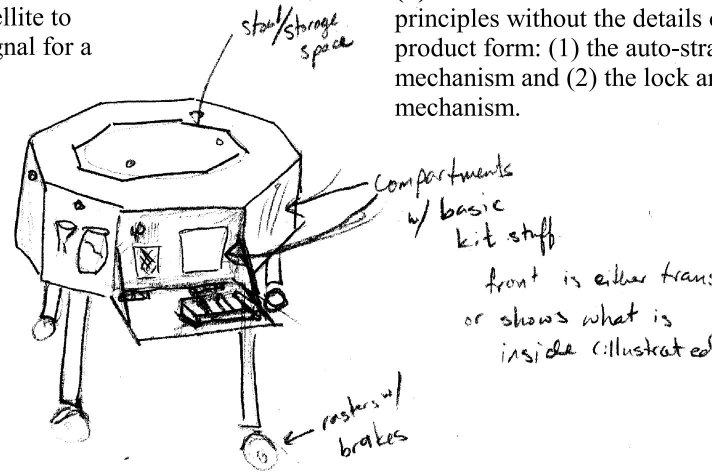
We correlated the *variety* score with both the midterm project grade and the final project ranking in order to see if the generation of a large range of concept alternatives would correlate with proxies for good design concepts and high quality design outcomes.



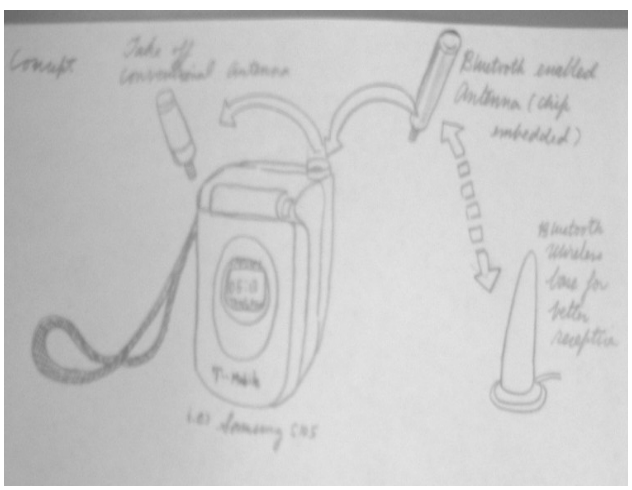


(a) Level 1. This sketch shows the underlying technology: using a satellite to search for optimized strength of signal for a cell phone.

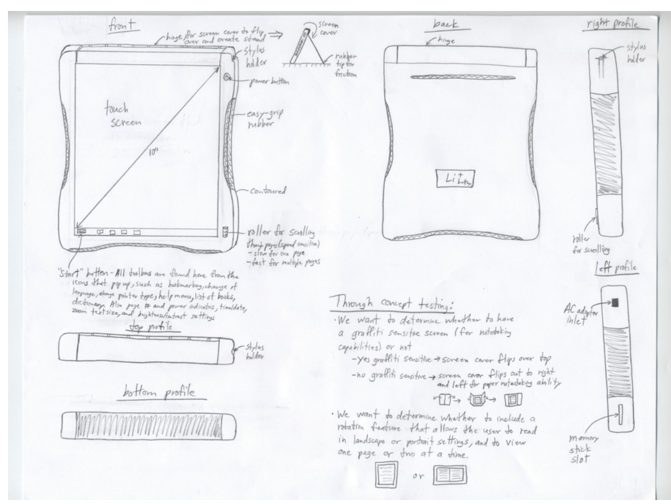
(b) Level 2. This sketch shows working principles without the details of the product form: (1) the auto-strapping mechanism and (2) the lock and release mechanism.



(c) Level 3. This sketch shows product form, along with annotation and rough shadings: a polygon container with wheels and a drop-down table.



(d) Level 4. This sketch illustrates and details product features: cell phone with separate antenna and base station.



(e) Level 5. This sketch shows the entire product form. Narrative explanations on navigation for this PDA book reader provided.

Figure 8: Sketches with five levels of detail.

Table 1: Variety scores of each team.

	Variety Score	Midterm Project Grade	Final Project Ranking	Total Number of Sketches
Team A	12.89	9.5	1	132
Team B	13.97	9.5	2	93
Team C	10.46	8.5	12	63
Team D	9.06	8.5	8	48
Team E	9.69	8.5	13	62
Team F	9.89	10	5	83
Team G	8.50	9	3	35
Team H	9.34	9	10	52
Team I	9.28	7	11	27
Team J	6.24	7	7	68
Team K	5.86	6	6	53
Team L	8.17	9	4	70
Team M	3	6	9	26

Table 2: Correlation coefficients between design data and design outcome.

	Variety Score	Total Number of 3D Sketches	Total Number of Sketches	Midterm Project Ranking	Final Project Ranking
Variety Score	1	0.275	0.599	0.724	0.121
Total Number of 3D Sketches		1	0.341	-	0.577
Total Number of Sketches			1	-	0.533
Faculty Midterm Project Ranking				1	0.570

Correlation with Design Outcome

The Spearman's rank correlation for nonparametric populations was employed to test for correlations between varies type of design data and design outcome in this study. For a population N = 13, the correlation coefficient R_s must be greater than 0.481 for a significance level of $\alpha = 0.05$. Table 2 shows the correlation coefficients between variety score, total number of sketches, total number of 3D sketches, and midterm project ranking or final project ranking. "Dashes" in the table represent uninformative correlations; for example the correlations between the total number of sketches throughout the semester with the grade at the midterm of the semester.

Our study demonstrates that the *variety* score and midterm project grade are strongly correlated in a statistically significant way, while *variety* score and final project grade are positively, but not significantly, correlated. This result is of interest because it suggests that a high variety of design concepts increase the likelihood of coming up with good concepts as measured by the midterm evaluation of the project that took place right after design stage 2. This result also suggests that good concepts might be poorly implemented in subsequent development phases [18]; for example, although Team C and team E achieved high variety and quality of concepts at the midterm, they ended up with low final project ranking.

Table 2 also shows that there is a statistically positive correlation between the total number of sketches and the final project ranking.

To further investigate the predictability of the design outcome with the combined evidence from both variety scores and total number of sketches, a multiple correlation on these three variables $R_{1.23}$ was calculated. The value of the multi-correlation coefficient was statistically significant at 0.543. Thus, the combination of the total number of sketches and the *variety* score positively and significantly correlated with design outcome; this combined measure was a stronger predictor than either alone. This applies to the combination of the total number of 3D sketches and the variety score in relation with the design outcome as well, the multi-correlation coefficients for these three variables is 0.578, which is statistically significant.

We also studied the evolution of the correlation between the total number of sketches and the total number of 3D sketches per design stage with final project ranking over the course of the term. Fig. 9. shows that there was an increasing positive correlation between the total number of sketches and the final project ranking as well as between the 3D sketches and the final project ranking, but they were statistically significant only in the third design stage. This suggests that the quantity of sketching overall and 3D, in particular, has a trend toward increasing the likelihood that good ideas are formed [15], the trend becoming statistically significant as the design progresses. This likelihood of success also increased when the *variety* of early concepts was high. Similarly a good starting trend will be offset by a concept selection decision that leads to a concept that is not physically feasible or competitive [16]. This suggests that elaborating product concepts during detailed design and development (design stage 3) demonstrated by producing more sketches is of equal or even more importance in achieving a good design outcome.

Furthermore, the total number of 3D sketches accumulated throughout the design cycle was significantly correlated with final project ranking with R_s =0.577, but not significantly

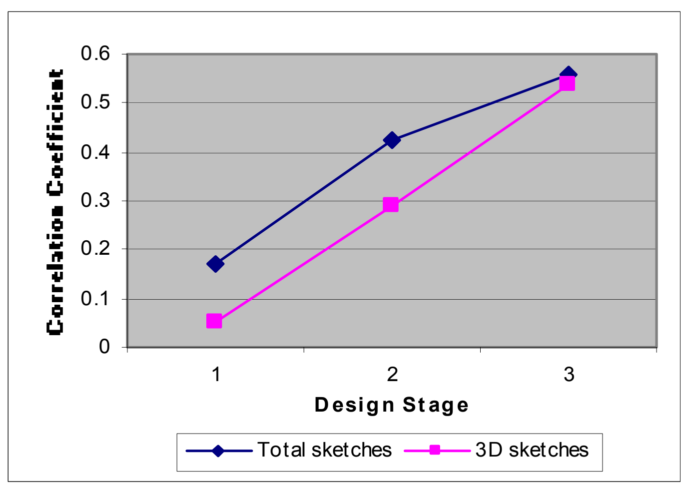


Figure 9: Correlation coefficients between total or 3D sketches and design outcome.

correlated with the total number of sketches (R_s =0.341) as shown in table 2. This suggests the creation of 3D sketches in the design cycle have a positive effect on design outcome. We also studied the date at which sketching first began in each team, but found no correlation between the time a team started sketching and the design outcome.

For the other types of sketches in the metrics we defined in the "methods and test bed" section, there are either not enough sketches for that particular type, or there are no statistically significant correlations between the volume of one type of sketch and the design outcome. However, we observed a strong correlation between prescriptive sketches and final project rankings at design stage 3 (R_s =0.582). Clearly, a large number of prescriptive sketches at the end of the design process is an indicator of a well-developed design and thus the correlation with the final project ranking is not surprising.

Correlation With Individual Performance

Finally, sketching by individual team members was measured by the correlation between the total number of sketches in each team member's design journal and her/his final individual course grade. The grades were based on a combination of factors including homework assignments, team project scores, and peer evaluation scores. Thus, the grade was an indicator on how well a student learned the product design process and how well they performed in their team projects. The Spearman's correlation coefficient was 0.397, which was greater than the critical value of 0.221 with 55 degrees of freedom for a significance level of $\alpha = 0.05$. This suggests that the creation of more sketches in the design process has a positive effect on individual student's performance. Granted that this result only reveals a statistical correlation and not causality, it does raise the question of whether encouraging students to sketch more in their design journal will increase a student's learning and design experiences.

To understand the impact of gender in sketching activities, we studied the average number of sketches per male/female student by type of sketch. For a total of 57 students in this course, 13 of them were females. Surprisingly we didn't observe any significant difference between these two groups. Our results showed that there was a significant correlation between the number of sketches created by each male student and their final individual course grade (R_s =0.391, α = 0.05, critical value = 0.251). However, we found no significant correlation among female students, probably due to the fact that their numbers were small.

Another interesting preliminary study we conducted is the influence of personality in sketching activities. All students in the course are required to take a Myers-Briggs Type Indicator test [19]. Based on the MBTI test result we studied the average number of sketches for each pair of Myers-Briggs dimensions (Extraversion/ Introversion, Sensing/ Intuition, Thinking/ Feeling, Judgment/ Perception). Results showed that intuitive students sketched 12% more than sensing students on the average. No other patterns emerged based on personality type. Future research is needed to fully understand the impact of gender and personality on sketching activities, individual performance and design outcome during the product design process.

CONCLUSION AND FUTURE RESEARCH

The paper identifies a comprehensive list of metrics for characterizing and evaluating design sketches: *generation*, *type*, *medium*, *representation*, *annotation*, *variety* and *level of detail*. In addition, the results show how sketching evolves over time, in particular, how different types of sketches predominate at different design stages. Results show that:

- The largest number of sketches was produced during the conceptual design stage 2 as compared to the other two stages considered.
- Although the majority of sketches were "new sketches" throughout the design life cycle, there were considerable more sketches that were "vertical transformations" of a previous sketch in design stage 3 than "lateral transformations" of a previous sketch.
- The largest percentage of sketches was traditional freehand sketches in the "medium" category. However, CAD drawings emerged in the conceptual design stage 2 and greatly increased in the final design stage 3.
- As the design process proceeded, students tended to sketch more in 3-dimensional space and less in 2-dimensional space.
- Text (labels and narratives) was the dominant form of annotation in sketches for all three stages. The percentage of text annotations, however, decreased over time, while lists, dimensions and calculations increased.
- There was a marked increase in the level of detail of the sketches as design moved from the initial preliminary stage through conceptual to detailed design.

Furthermore, the results showed that *variety* was an effective measure as to how well designers explored the design solution space. There was a statistically significant correlation between the variety score and the midterm project score. Not surprisingly, variety scores didn't correlate with the final project grade in a significant way. But combining evidence from both the number of sketches and the variety score achieved a significant positive multi-correlation with project ranking. This supports the hypothesis that the combination of high quantity and variety of product concepts produces good design outcomes.

Finally, the study confirms that the total number of sketches and the use of 3D representations and prescriptive sketches in later design stages have a positive effect on the design outcome. Individual performance was also correlated positively and significantly with the total number of sketches.

This study has provided insights into the role of sketching in the design process; but it has raised many questions as well. Several inter-related research extensions are discussed below. Further research work will focus on integrating these other aspects of the design process. We will also perform studies at a range of expertise levels (freshman, senior, graduate, experienced industry designers) and with classes that have a higher multidisciplinary composition.

Superior Design Outcome

In this study, we used instructor rankings as indicators of the design outcome. The instructor's final project ranking involved information from a jury of design experts, a review of the intermediate documents during the design process and peer-evaluations. Yang's study [15] used a competition grade as another indicator of design outcome. Neither metric tells the whole story. They don't measure the originality or creativity of the product or the team. They don't measure how effectively customer needs were met, nor whether the constraints or needs were met in a particularly simple or elegant way [12].

Impact of Sketching on Creativity and Innovation

Although we found a correlation between metrics of sketching and design outcomes, we can make no causal statements. The research begs the question: Does sketching facilitate creative thinking and better design outcomes?

Design is thought of as being inherently creative and relatively unstructured drawings or sketches are considered to play an essential role in generating creative outcomes. Shah et al. [16] defined *novelty* to measure how unexpected and unusual an idea is. Further research is needed to study the role of sketching in producing creative design environments and outcomes. In particular it would be interesting to investigate the tension between the potential benefits of sketching in highlighting and sharing design conflicts, with the potentially limiting role sketches play by limiting reinterpretation when compared with a purely textual or verbal description.

Impact of Sketching/Verbal Skills and Preferences

Another question motivated by this research is: does a student's or a team's collective sketching skill impact the quality of the design outcome? One might hypothesize that enhanced sketching skills improves the quality of the solution and shortens the process of finding a solution as it "binds fewer memories" [4]. Measures of prior sketching skills were not collected for this study, but will be included in future research. If sketching skills are positively correlated with success, will developing students' sketching skills improve design outcomes? Or is good sketching a matter of self-selection and correlated with other design attributes, such as innate artistic ability or personality traits? With the move to replace drafting and drawing courses with CAD courses, training on sketching has been greatly reduced, if not eliminated, at the university level. Ullman argues that even though a good percentage of an engineer's graphic representation is informal sketching, drafting and CAD are the main topics taught in graphical communication courses for engineers. Most engineers receive no formal training in sketching. It is often assumed to be some natural ability [5].

Similarly, what are the roles of verbal skills and preferences in producing good design outcomes? Can strong verbal skills replace or compensate for lack of sketching skills in the design process? Or does a high performing team need a complement of skills and preferences [19]? Or do other socio-cognitive factors, such as confidence level and outcome expectations, overpower both verbal and visual skills and preferences [20]?

Schutze's study shows that subjects who solved their test design problem with partial support with sketching achieved a significantly higher solution quality compared to those whose problem solving was entirely mental. The quality was even higher for the test group that received full sketching support compared to the other two groups [4].

One could hypothesize that some designers may make minimal use of drawings because they have developed effective means of using abstract conceptual knowledge or verbal imagery as the foundation from which to develop and define the representation of a specific physical artifact [12]. Cognition research shows that the types of knowledge accessed from words and images are different. Words prompt access to conceptual and prepositional knowledge while images draw upon perceptually based knowledge – knowledge about materials, forms and precedents. Creating verbal representations can make visual/imagery-based representations inaccessible [10].

If verbal activity and imagery do access different types of knowledge in design contexts, then there may be subtle interplays between the two, particularly in group communication and design activities. We observed in our study that fewer sketches were produced during the initial design stages compared to the other two downstream stages. In our prior research, using a linguistic analysis of the text of design documents, we found a correlation between product success and "shared vision" as measured by the semantic coherency of the documents [21]. Others have also reported on the role that verbal explorations, understandings and even "arguments" play in initially framing a design problem [12, 17, 23-24]. Indeed it may be that design teams are more effective because talking is a natural part of the process and because the combination of talking and drawing inherent in a design group maximizes the accessing of both abstract knowledge and knowledge about physical forms and materials [12]. Suwa's study discusses how sketching can be a good medium for a reflective conversation [9].

Personal Contributions and Team Size

We also investigated the size effect of the team and the design outcome. Surprisingly there was no statistically significant correlation between the size of a team and the total number of sketches that they created (correlation coefficient = 0.124). However, some team members created noticeably more or less sketches than others. Perhaps the work was divided up and each member played a different role in their team, allocating conceptual design or sketching to those with strong abilities in these areas. Perhaps team members contributed differently depending on whether they were visual or verbal thinkers. Purcell hypothesizes that some individuals may be responsible for the conceptual design while others focus on developing the idea [12]. We are currently audio taping design teams, collecting meeting visuals and analyzing their email logs using social network theory and speech act theory to identify factors that contribute to a creative environment, including the roles that individuals play in improving the "ecology of innovation" of the group [25].

Archival and Retrieval of Design Documents

Empirical studies show that up to two-thirds of the marks made on paper during conceptual design activities are sketches [26]. Since sketching plays such a key role in the design process, especially during the conceptual design stage, distributed specifications should accommodate visual material in addition to textual information [6]. In our future studies we will ask the students to archive all of their documents, including those produced during informal meetings. We will also ask the students to better document the evolution of their ideas.

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