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Observations on concept generation and sketching in engineering design

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Abstract The generation of ideas is an essential element in the process of design. One suggested approach to improving the quality of ideas is through increasing their quantity. In this study, concept generation is examined via brainstorming, morphology charts and sketching. Statistically significant correlations were found between the quantity of brainstormed ideas and design outcome. In some, but not all, experiments, correlations were found between the quantity of morphological alternatives and design outcome. This discrepancy between study results hints at the role of project length and difficulty in design. The volume of dimensioned drawings generated during the early-to-middle phases of design were found to correlate with design outcome, suggesting the importance of concrete sketching, timing and milestones in the design process.

Keywords Concept generation · Sketching · Design process

1 Introduction

The generation of ideas is a key activity in the design process. This study focuses on one idea generation method known as brainstorming (Osborn 1963) which has been widely adopted in product design and development in industry (Sutton and Hargadon 1996; Kelley and Littman 2001). Brainstorming consists of a set of broad, process-driven guidelines that can be applied in many contexts. However, Shah et al. (2000) points out that the results of brainstorming can be "unpredictable." This study focuses on measuring a single aspect of the brainstorming process through one of its main guidelines: generate as many ideas as possible. By broadening the initial pool of ideas, the assumption is "quantity yields quality."

Osborn's rules have previously been examined to understand the role of social situations in creativity (Diehl and Stroebe 1991; Paulus et al. 1995; Paulus 2000). These experiments consider brainstorming through creativity exercises of brief duration and scope using subjects who generally do not have experience in design. This approach is valuable in that it limits confounding factors in the analysis of the creative process. This paper considers concept generation from another perspective, that of engineering design in multi-week long projects involving engineering design students.

This paper examines three hypotheses related to concept generation in design and builds on preliminary research by the author (Yang 2003). These hypotheses were formulated in the context of engineering design courses, and are intended to help design practitioners improve their creativity and design outcomes as well as assist educators in teaching design:

Hypothesis 1 The quantity of concepts generated at the beginning of a design project correlates with design outcome.

It has been suggested that the generation of more ideas initially leads to a higher incidence of better quality ideas. It may be further surmised that having a higher quality idea in the early stages of design process may be more conducive to a better final design outcome. Do individuals who generate more ideas also have better final design projects?

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This paper examines this question through the quantity of ideas generated by brainstorming. It also considers concept generation at a lower level through morphology charts which are hierarchies of alternative embodiments that can fulfill each of a device's functions (Zwicky 1969).

Hypothesis 2 The quantity of sketches generated during a project correlates with its design outcome.

Sketching is an integral part of the engineering design process. Sketches are representations of a design, but research suggests that the process itself of sketching is a fundamental element of design thinking (McKim 1980; Ullman et al. 1990; Schön and Wiggins 1992; Nagai and Noguchi 2003). In particular, the act of sketching is thought to be critical to generating concepts (Goldschmidt 1994; Goel 1995; Suwa and Tversky 1997; Purcell and Gero 1998; Verstijnen et al. 1998). Tovey et al. (2003) refer to sketching as a "language for handling design ideas." The studies of Romer et al. (2000) posit that sketching is useful as a way to mentally offload concepts during complex design activity.

Observations of industrial practice suggest that design success is closely linked to realizing an idea through drawing and prototyping (Schrage and Peters 1999). Other research has assessed sketching to determine possible links to design outcome. Schütze et al. (2003) found that designers who were allowed to sketch during the design process produced a higher quality solution than those who were not permitted to. However, Bilda et al. (2006) suggest that sketching is not essential for design, although the more basic activity of mental imagery may be still be critical. Song and Agogino (2004) found significant correlations between sketch volume and design outcome in a product development course. Yang and Cham (2007) found no links between drawing skill and design outcome, but did show that skilled sketchers tended to draw more overall.

This paper investigates the quantity of design sketching as another way to infer concept generation volume. Sketches are divided into two categories: dimensioned drawings and non-dimensioned drawings. Dimensioned drawings are of interest because they may represent ideas that are further along in the design cycle and are therefore more developed than non-dimensioned ones.

Hypothesis 3 Increased sketching at the beginning of the project, rather than at the end, correlates with better design outcome.

Designers can, and do, form ideas throughout the design cycle. Concepts may occur under formal circumstances (for example, to meet a milestone) or more spontaneously, as a classic "eureka" moment. However, concurrent engineering holds that design decisions made in the early, conceptual phases of design have greater impact on overall design than those made later on (Winner et al. 1988). This study observes whether sketches generated earlier or later on in the design cycle have different correlations with design outcome.

2 Related work

2.1 Measures of creativity

Idea quantity, or fluency, is but one of several measures for creativity. Other metrics for concept generation include flexibility, or the range of ideas, and originality, or novelty of idea (Guilford 1959). Shah et al. (2003) define formal metrics including novelty, variety, quality, and quantity which have been adopted by other researchers (Song and Agogino 2004; Chusilp and Jin 2006). This study focuses on primarily on quantity in part due to its relative objectivity as a measure across a range of idea representations such as sketches and textual lists of ideas.

2.2 Types of sketches

Sketches may be considered from several perspectives. Ferguson (1992) classifies three types of sketches in terms of their intended purpose: the thinking sketch serves as a reflective medium, the prescriptive sketch acts as a blueprint for design work, and the talking sketch supports design collaboration.

Sketches may be categorized by the design progression they represent. van der Lugt (2005) examines sketches as a mechanism for reinterpretation of an individual designer's ideas. Goel (1995) defines "lateral transformations" as incremental changes that build on a previous idea, while "vertical" ones result in a more detailed version of an earlier sketch. McGown et al. (1998) and Rodgers et al. (2000) label categories based on the physical elements of engineering sketches:

- Level 1: A simple monochrome line drawing that does not include shading or annotations
- Level 2: A detailed monochrome line drawing with annotations but no shading
- Level 3: A Level 2 drawing with shading to suggest 3D form
- Level 4: A Level 3 drawing with more gradations of shading and possibly color to emphasize 3D form
- Level 5: The most "realistic" type of sketch includes extensive shading and annotation

The sketches described in this paper can have aspects of all of the above categories of sketches.

3 Methods

3.1 Test bed

The test beds for these experiments were two project-based, undergraduate mechanical engineering design courses at the California Institute of Technology. In all three courses, teams were provided with identical sets of materials from which to prototype.

The first course was in advanced engineering design. Data was collected from two separate years of this course. The advanced course had twenty-four students in one year ("Course 1") and twenty-three in the next ("Course 2"). In both, teams of two students were presented with an open-ended, ill-defined design challenge such as a robotic capture-the-flag game. They were required to develop conceptual designs and fabricate a fully functional electromechanical device in the engineering machine shop. Potential design solutions could range from simple three-wheeled cars to robotic arms to combinations of custom mechanisms. The breadth of design scope provided ample opportunity for sketching many aspects of various design concepts. At the end of the ten-week course, teams competed against each other in a double elimination contest held before the entire campus. A single winner emerged. Example projects are shown in Fig. 1, along with a representative sketch from the corresponding logbooks. Note that though students worked and competed in pairs, they were expected to produce their own separate devices that were assessed independently from their teammate's.

The second course was an introduction to design comprised of thirty-three students ("Course 3") which was a pre-requisite to the advanced course. This course included a three-week long, open-ended design challenge in which students were asked to design and build a solution using "soft" materials, such as foamcore, to pop a helium-filled balloon suspended over a large water pond. Students worked in teams of three to five and were graded both as a team and as individuals. Sample projects are shown in Fig. 2, along with a drawing from the associated logbooks. As in the other course, design solutions could span a wide range of possibilities including hooking and grasping mechanisms and drivable boats. The range of potential solutions allowed a variety of sketches and ideas to be developed over the duration of the projects.

3.2 Design data

3.2.1 Brainstorming and morphology charts

Concept generation was examined through brainstorming and morphology charts. Brainstorming took place in the first third of the project for the Introductory Course. Each design team was presented with the design problem and then asked to generate and write down conceptual design alternatives in class and on their own over a span of a week. The number of brainstormed ideas generated by each students was counted.

Morphology charts were created in all three courses. Morphology charts require a more systematic, lower level

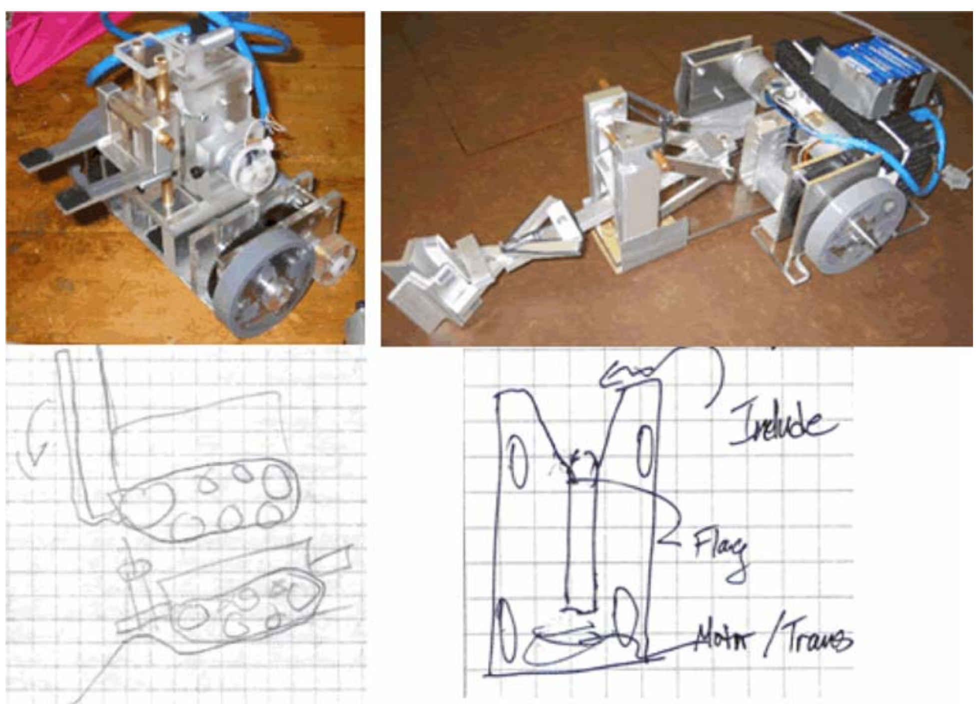

Fig. 1 Electromechanical design projects from the advanced design course (Courses 1 and 2). Below each photo is a sample sketch from the logbooks kept for each project

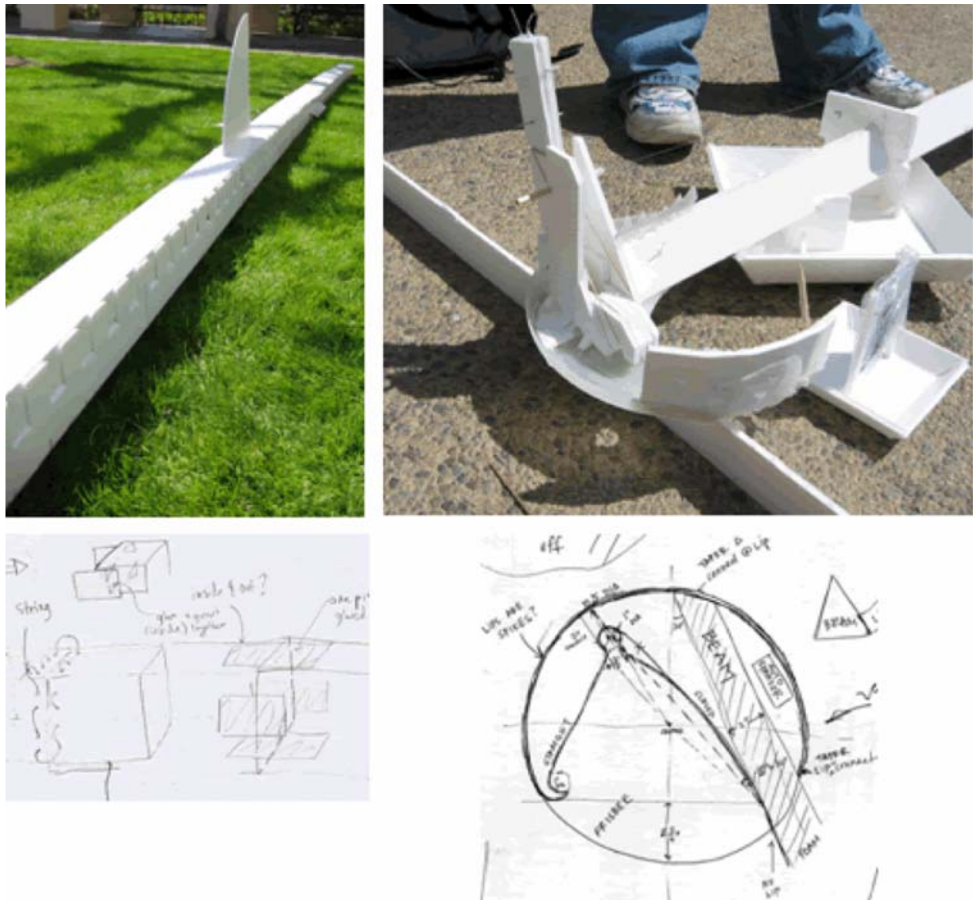

Fig. 2 Sample projects constructed of foam core from the introductory design course (Course 3). Below each photo is a sample sketch from the logbooks kept for each project

enumeration of concepts than brainstorming. Early in the projects for all three courses, each team developed a chart of the desired functions of their device, along with possible approaches to achieving those functions. For example, if the desired function was to “block an opponent,” ways to achieve that goal might be to “drive into the opponent” or “push the opponent.” Most of these embodiments were illustrated with thumbnail diagrams, and all included brief text descriptions. The total number of morphological embodiments was counted.

3.2.2 *Sketching and logbooks*

Paper-based design logbooks were kept by each student over the life of the project. Logbooks can be a comprehensive record of a student’s design process and thinking. The information archived in the logbooks varied widely in form, including detailed descriptions of work, plans for fabrication, engineering calculations, and sketches of many types and levels of detail.

Individual drawings in each logbook were counted and indexed by date and by whether it was dimensioned or not. Drawings were considered dimensioned if they included numeric labels for parameters such as length, width or diameter. Such drawings may be interpreted as a step towards making a design more concrete.

As with any informal information, there is ambiguity as to what constitutes an individual drawing, and the goal was to be consistent between logbooks. In nearly all cases, however, distinct objects were obvious because of white space separation or clear annotations (such as indicating text or arrows) in the sketch. Ullman et al. (1990) uses “marks on paper” to refer to both sketches and annotation in order to capture the ambiguity inherent in defining design sketching. The quality of individual sketches was not considered, in part because other work suggests that sketch quality is not linked to design outcome (Yang and Cham 2007).

This study did not normalize for a student’s drawing ability or previous drawing experience. None of the students were given any sketch instruction. In Yang (2003), a survey was taken of one of the advanced courses (Course 1) to gauge the level of other relevant design experience that students might possess. The results of the survey showed that students generally felt they had above-average experience in engineering analysis, engineering intuition, engineering fabrication and arts and crafts. Students also self-reported below-average experience in drawing, tinkering, and construction.

Table 1 Summary of design courses and type of data captured

Design Course	Project length (weeks)	Design data collected		
		Brainstorming	Morphology	Sketch
1 (Adv)	10		×	×
2 (Adv)	10		×	×
3 (Intro)	3	×	×	

Table 1 summarizes the types of design data collected in each course.

3.3 Design outcome evaluation

Two indicators of design outcome were employed. The first was the individual final grade, counted in points, for each student. The maximum number of points possible was 100, and was based on overall performance over the 10-week period. For the introductory class (Course 3), project grade was also considered. Note that the final grade includes student effort for two other projects unrelated to the first project.

The second indicator, applied only to the advanced courses, was each team's final ranking in the contest. Contest performance was based on the number of rounds of competition that the team was able to win. The more rounds won, the higher the rank. Contest performance was decoupled from the final grade itself. It was possible for a team to perform poorly in the contest but earn a good grade, and vice versa. One reason for this is that the primary goal of the class is to teach engineering design and design process, and a student could demonstrate an excellent grasp of design process but still rank low in the contest.

4 Results and discussion

4.1 Type of sketching

A total of 4,008 sketches were counted in the logbooks. 61.4% included dimensions and the remaining 38.6% did not. The dimensioned sketches were generally considered "prescriptive" sketches in that many of them were likely meant as blueprints for fabrication. The remaining sketches were virtually all "thinking" sketches (Fig. 3). In these courses, logbooks were primarily a device for capturing the thinking of the individual designer, and this function was borne out in the sketches found in the logbooks. This is also consistent with the findings of Song and Agogino (2004).

Although the advanced course students were asked to document their design process in paper logbooks, students were not prohibited from using other media for visualizing their ideas, and access to CAD tools was freely available to all students. In one of the advanced courses, one out of the twenty-four students used CAD tools to create both dimensioned and non-dimensioned drawings. In the following year, six of twenty-three students employed CAD, although it is not clear why more students chose to do so. In this study, CAD drawings were treated in the same manner as hand sketches under the assumption that they are still representations of design thought. Also, at the time Ferguson wrote his book, Computer-Aided Design (CAD) tools were not as ubiquitous as they are today, and it would be reasonable to think many engineering designers create "prescriptive" sketches for themselves rather than a third party to formalize.

There are some challenges in judging sketches *post facto* for two reasons. First, without explicitly asking the designer's intended purpose with each sketch, the observer can only guess what the intention is. Second, a sketch may serve multiple purposes. For example, though many of the logbook sketches could be characterized as "thinking"

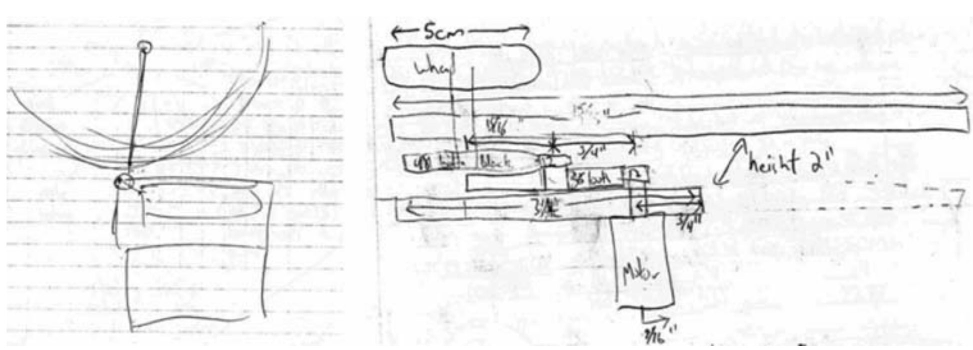

Fig 3 Example "thinking" sketch, Level 1 detail from logbook (*left*). Example "prescriptive" sketch with Level 2 dimension details on *right*

sketches, their design work was performed in the context of the classroom, so it would be reasonable for students to expect that others (teammates or teaching staff) might refer to their sketches in the way they would a "talking" sketch. Evidence of this is seen in the way some sketches were annotated in first person narrative.

Although in most situations it was clear what mechanical component a particular drawing represented (for example, a wheel or a gear), the content of each sketch was not tracked. Since many of these logbook sketches were "thinking" sketches, it is difficult to interpret what the intention of the sketch was. A jumble of lines may be meaningless to the external observer, but hold important meaning for the sketcher. The quality of idea represented in a sketch was likewise not tracked.

Almost all drawings found in the logbooks were Levels 1 and 2, and occasionally Level 3, meaning that they were primarily line drawings with limited annotation and sometimes shading. It is important to note here that the levels of detail outlined by McGown et al. (1998) were based on observations of engineering students who had gone through art and industrial design training as part of their core curriculum. In comparison, the designers observed in this study are relative novices in sketching.

4.2 Concept quantity and design outcome

Hypothesis 1 The quantity of concepts generated at the beginning of a design project correlates with design outcome.

Table 2 shows that the quantity of ideas brainstormed had a statistically significant Spearman correlation (R_s) with both the three-week project grade and the overall final grade for the term.

Table 3 shows correlations between the quantity of morphological alternatives with both final grade and contest performance for Courses 1 and 2, and with grade only for Course 3. The number of morphological alternatives includes embodiments from all hierarchy levels. Note that for Course 1, $N = 20$ rather than 24 because of data unavailability, so for a significance level $\alpha = 0.05$, R_s must be greater than 0.377. Course 2 had even less data available for analysis ($N = 12$). Course 3 includes two design outcome measures—the final grade for the course, and the grade for the three-week project only.

Table 2 Correlations between brainstormed ideas and grade for Course 3 (introductory course)

	Correlation coefficient, R_s	
	Project grade	Final grade
Total ideas brainstormed	*0.48*	*0.33*

$N = 33$, $R_s = 0.291$ for $\alpha = 0.05$

Table 3 Correlation of morphology alternatives for all courses

	N	R_s	Correlation coefficient, R_s	
			Grade	Contest
Course 1	20	0.377	0.19	0.160
Course 2	12	0.503	0.020	−0.07
Course 3	33	0.291	*0.61* (project)	N/A
			0.34 (final)	N/A

For Courses 1 and 2, the total morphological alternatives do not correlate positively with either grade or contest performance. In contrast, the introductory course (Course 3), correlated statistically significantly with both final and project grade.

Possible explanations for this difference between the two courses could include sample size, length of project, and level of prototyping skill required for the project. Many issues can arise during the development and fabrication that are not considered or are unforeseeable in the early, conceptual stage. In the introductory course, students need only have rudimentary soft prototyping skills, and the project is only three weeks long. The likelihood that their design will change is lower than for the advanced courses which require some level of skill and training in the machine shop and whose project lasts three times as long. The response to this hypothesis then is a "maybe." In this case of a shorter, less involved design project such as found in the introductory course, this hypothesis holds true. However, in the more involved, longer duration project such as found in the advanced courses, this hypothesis was not found to be the case.

It should be pointed out that this finding does not necessarily mean that the number of ideas is a cause of project success, only that the two variables tend to increase and decrease together. Other factors that may also be linked to the final outcome of design will be discussed in Sect. 5.

4.3 Sketch quantity and design outcome

Hypothesis 2 The quantity of sketches generated during a project correlates with its design outcome.

No statistically significant correlations were found between the total quantity of either dimensioned or total sketches of any type and final grade or contest ranking for the three courses. Overall, prolific sketchers were no more likely to have good design outcomes than those who did not sketch as much. This diverges from the findings of Song and Agogino (2004), and it is theorized that this is due to the differing natures of the design projects. The projects studied by Song were primarily product design projects with an emphasis on market studies. In contrast, Courses 1 and 2 focus on engineering design, with an emphasis on physical prototyping. This phenomenon is examined in closer detail in the following section.

This paper's findings may be further considered in light of the work of van der Lugt (2005) who determined that idea generation was not related to better design outcomes unless designers "worked" the sketch through re-interpretive cycles. In this paper, the re-interpretation of sketches was not tracked, but may merit further examination in future work.

4.4 Sketching over time and design outcome

Hypothesis 3 Increased sketching at the beginning of the project, rather than at the end, correlates with better design outcome.

Figures 4 and 5 show the average number of sketches plotted by time in the advanced courses. The lower, darker section of each column represents the dimensioned drawings, and the entire column shows the total number of drawings (dimensioned and non-dimensioned).

The general trend in both courses is the same—fewer overall drawings in the beginning, more in the middle, and a drop off at the end of the project. There are also a proportionately greater number of total drawings during the first part of the term as compared to the remainder of the term. It is observed that the proportion of dimensioned sketches to the total number of drawings starts off low and increases towards the middle of the project. Taken together, these trends may indicate abstract conceptual design activity early in the design cycle and more prototyping in the later stages of the design cycle.

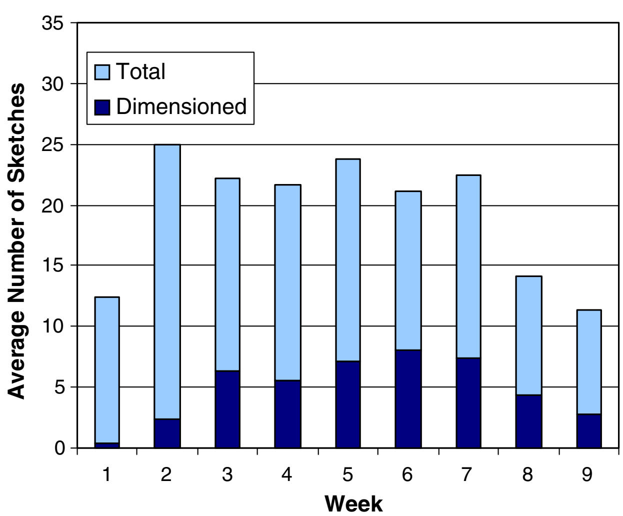

Fig. 4 Average weekly total and dimensioned sketches for Course 1 (Advanced Design)

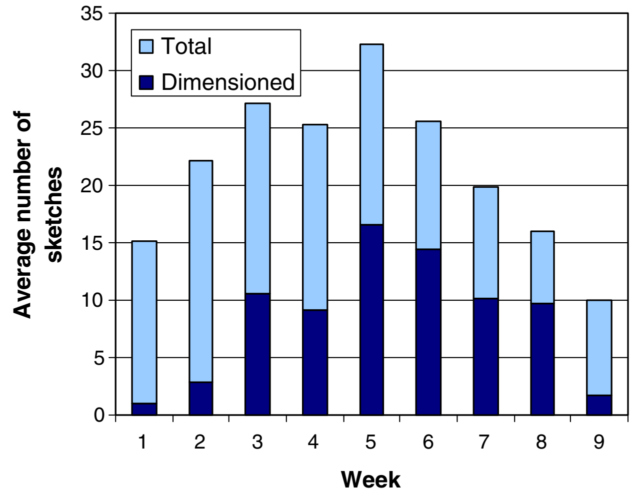

Fig. 5 Average weekly total and dimensioned sketches for Course 2 (Advanced Design)

There are differences, however, in when the peak number of drawings/sketches occur. We see that for the first advanced class (Course 1), the peak starts almost immediately in the second week. For the other advanced class (Course 2), the peak is not reached until the fifth week. A possible explanation might be due to the design milestones in which students present their work to the teaching staff, typically in the form of drawings and prototypes. Milestones serve as a project management guideline for the students, as well as a way for teaching staff to monitor progress. Interestingly, the timing of design milestones within the project is nearly identical in both courses.

Figures 6 and 7 list the Spearman correlation coefficients (R_s) for the average total non-dimensioned and dimensioned drawings per week correlated with final grades and contest performance each week of the term. Dotted horizontal lines show the threshold for statistical significance.

Figure 6 shows that dimensioned drawings and final grades are correlated in a statistically significant way during the first three weeks of the design cycle. The total number of drawings is also significantly correlated with grade during the third week, and in the first week with contest rank. This result is notable because it shows that the creation of more concrete dimensioned drawings early in the design cycle has a positive correlation with design outcome.

The trend in Fig. 7 is somewhat different. Dimensioned drawings correspond in a statistically significant way in the third and fourth weeks and total drawings correlate with contest performance only in the fifth week. In this case, dimensioned drawings are still important, but not until

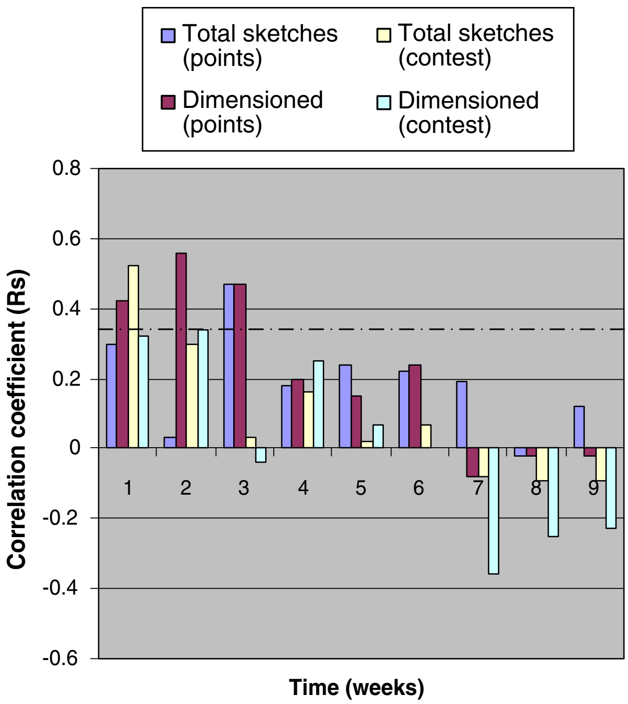

Fig. 6 Correlations between total and dimensioned sketches by week and design outcome for Advanced Course (Course 1). $N = 24$ and $R_s = 0.344$ (denoted by *dotted line*) for $\alpha = 0.05$

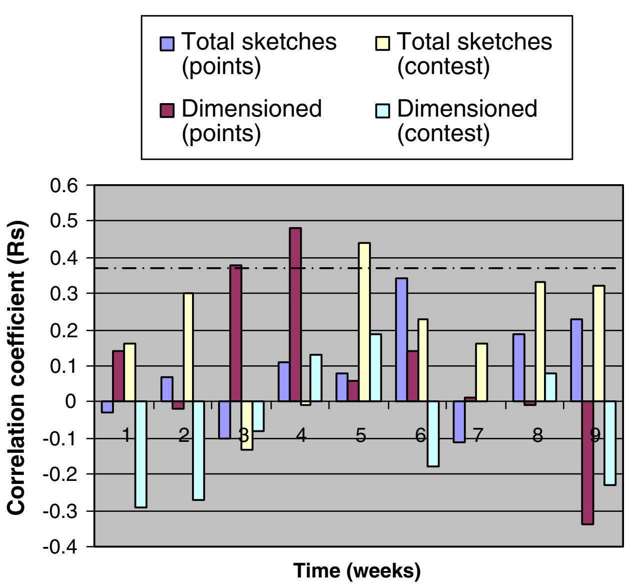

Fig. 7 Correlations between total and dimensioned sketches by week and design outcome for Advanced Course (Course 2). $N = 21$ and $R_s = 0.370$ (denoted by *dotted line*) for $\alpha = 0.05$

slightly later in the early-to-middle phases of the design cycle.

In both cases, the correspondences are roughly coincident with each course's peak sketch volume in Figs. 6 and 7. These peaks occur around the periodic design reviews in which students must present their project work to the teaching staff for feedback. Average student sketching activity is at its highest when it is most strongly correlated with design grade. One possible explanation is the nature of design performance. Both final grades and contest ranking are somewhat relative measures. While it is possible that all students in a course can earn an "A," it is more likely that students will receive grades that fall along a distribution relative to each other. At the same time, the contest itself is intended to produce relative rankings, with clear standings. It makes sense, then, that the relative efforts of a student during peak design activity might be associated with design outcome.

Interestingly, the correlations with grades tend to become more negative over time. Correlations with design activity early in the design cycle are more positive, and later in the design cycle are more negative, which suggests that last minute efforts at sketching are not consistent with a good outcome.

In these cases, the proposed hypothesis is shown to be true. In addition, the role of milestones in planning design work may be important, and falling behind in design is linked to poorer outcomes.

5 Conclusions

5.1 Concept generation and sketching

Concept generation measured in the form of morphology charts showed a statistically significant correlation with both project and final term grade in the introductory course. However, morphology charts in the advanced courses did not show a statistically significant correlation. This may be due in part to the inherent differences of methods to generate concepts. Strictly speaking, brainstorming is meant to generate a wide range of concepts, while morphology charts are only intended to enumerate mechanisms for achieving specific functions. The key difference in these two courses is the timing of concept generation and design outcome. A shorter elapsed project time combined with less emphasis on detailed fabrication in the introductory class suggests that the role of idea quantity is less important the further along in the design cycle outcome is measured.

One of the unexpected findings of this study was the role of timing in concept generation and sketching. Data from the advanced courses shows that dimensioned sketch quantity is significantly correlated to design grades in the first half of the design cycle.

Total sketching volume measured at the end of the term, including both dimensioned and non-dimensioned drawings, did not correlate with graded design outcome or contest performance. This suggests that it is possible to produce copious drawings during the design process and still have an unsuccessful graded design. Likewise, it is implied that a designer can sketch very little overall and achieve a better design grade, as long as the bulk of dimensioned drawings (and perhaps prototyping) are created early on in the design process. This suggests that starting work early on a project is beneficial.

It should be noted that there can be a range of approaches to maintaining a logbook. Design logbooks capture a wide variety of information in a flexible way. Many students detail their design activity meticulously. For others, however, logbooks may not always be a complete record of design thinking. This may be due in part to the overhead involved with keeping a logbook. As one student put it, "I do design in my head" rather than write thoughts down.

5.2 Design outcome

Two design outcomes were used in this study: final grade and contest results. Only total sketching volume correlated significantly with contest results. This is interesting because in some ways, the contest simulates the conditions of real world design in that the situations in which a product is released are unpredictable, unlike a classroom setting that is controlled and "safe." While students were provided with as realistic a testing environment as possible throughout the term, the actual contest included technical issues that could not be replicated beforehand, such as electrical interference, as well as non-technical issues such as the stress experienced by contestants competing in front of their peers. However, unlike the real world, a contest is an artificial construct. In real-world design, there is rarely an absolute notion of winning or losing, and the definition of success is open to interpretation.

The final design grade in these cases is comprehensive and assesses the overall design process. In industry, a product can be developed following a "good" process but the result can still be thought of as unsuccessful. Contests, on the other hand, focus on end products instead of process. In either case, the development of appropriate design outcome measures that are viable for evaluation is an open area of design research.

5.3 Sketching and prototyping

Dimensioned drawings are a logical precursor to prototyping. These results suggests that prototyping earlier in the design cycle rather than later is linked to better design grades, perhaps because starting fabrication earlier leaves more time for iteration and refinement of a design.

In some ways, the correlation between early dimensioned sketching is somewhat counter-intuitive. The rules of brainstorming hold that designers should withhold judgment on a set of ideas before selecting one for further development and manufacturing. Concurrent engineering as well as system engineering posit that more time spent up front to understand the potential implications of design decisions downstream is beneficial to design. However, the results of this study suggest that selecting a design path and prototyping earlier on is preferable. This may have to do with the fact that the course being studied has a strong emphasis on prototyping a fully functional design. In fact, Yang (2003) found that the students who self-reported having prior engineering building experience and engineering intuition that correlated significantly with design outcome. The suggestion that earlier prototyping is consistent with better design results aligns with the findings of Ward et al. (1995). Ward examined the highly successful design and manufacturing process at Toyota Motor Company. Toyota's counter-intuitive approach at the time was to prototype many design alternatives before selecting one for full production.

5.4 Limitations

It should be emphasized that all three of the hypotheses included in this paper rely on the notion of correlation rather than causation. The products of the earliest stages of the design process, such as concepts and sketches, are not examined as the sole causes of a design outcome, but as co-occurrences with design outcome that may merit further study. One of the challenges is that numerous steps are involved in design beyond the formulation stage, including fabrication and testing, that may have little to do with the initial ideas generated. Furthermore, there may be interactions among these steps that introduce additional confounding factors.

At the same time, it should be pointed out that those designers who generate greater quantities of ideas or produce more sketches or start prototyping their projects earlier may possess characteristics that will facilitate stronger design outcomes. These designers may be more motivated, more creative, and perhaps better able to address the challenges of creating a more successful design, and thus produce a better design outcome.

6 Future work

This study draws on guidelines from design practice to correlate concept quantity and sketching with design outcome. However, this research is one of many efforts to better understand sketching and concept generation in engineering design. Future work will consider specific aspects of sketches that reflect cognitive elements of concept generation and sketching as found in Shah et al. (2000, 2001, 2003). In addition, there are a number of other types of design activity that merit study to understand their possible links to design. Song and Agogino (2004) point out the importance of considering other modes of design thinking, in particular verbal/textual cognition. Indeed, one of the best performing designers in the advanced class did little or no drawing, but meticulously documented his design activity in textual form.

A potential impact of this work will be derived from the development of relevant design tools to facilitate design information handling in design teams, both in the classroom and in industry practice. What are ways to formulate ideation methods and sketching guidelines so that they can help students become more effective designers?

The role of the design logbook as a design tool should also be examined. This work focuses both on individual and team design efforts, and in real-world design situations, products are often the end result of collaborative team work. Paper design logbooks such as used in these courses have long been employed to capture design knowledge, but electronic versions of these hold promise as tools to facilitate design thinking and process. There is relevant research in the area of electronic design notebooks (Lakin et al. 1989; Hong et al. 1994; Viste and Cannon 1995) that specifically supports design team collaboration. There exists a related body of research in textual design information analysis (Baya and Leifer 1994; Dong and Agogino 1997; Wood et al. 1998) as well as in electronic sketch capture (Yen et al. 1999) that may help design tools to be more intelligent and designers to be better designers. However, much work remains to be done in the research and development of design tools such as these. One current stumbling block is that such computational tools do not yet provide the same level of usability and critical affordances that simple paper and pen provide (Alvarado and Davis 2001). Some ideal features include portability, ease of sketching, and seamless integration with text tools. In addition, these tools need to allow ease of annotation of design sketches with rough dimensions and notes. More formal methods for visualization, such as CAD systems, are appropriate for representing later stage designs, but at the conceptual stage, the goal is to encourage agile, unimpeded concept generation (Kavakli et al. 1998). Work in this area focuses both on software to recognize sketches symbolically (Do et al. 2000; Kurtoglu and Stahovich 2002), as well as computer input devices to allow sketches to be created more easily (Dickinson et al. 2003).

Future work should focus on integrating aspects of these research areas to produce cohesive tools to support design teams and the design process itself.

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