Proceedings of DETC 2004
2004 ASME Design Engineering Technical Conferences
September 28 - October 2, 2004, Salt Lake City, Utah USA

DETC2004-57552

AN EXAMINATION OF PROTOTYPING AND DESIGN OUTCOME

Maria C. Yang
Daniel J. Epstein Dept. of Industrial & Systems Engineering
University of Southern California
Los Angeles, CA 90089
Email: maria.yang@usc.edu

ABSTRACT

The building of prototypes is an important part of the product design and development process. This paper examines factors in prototyping, including part count and time spent on design and fabrication activity, and their correlations with design outcome. The research questions asked: Do simpler prototypes mean a more successful design? Does more prototyping lead to better designs? Does the amount of time spent on a project, both overall and on different activities over a project cycle, relate to design success? One of the main findings of this study is that prototypes with fewer parts correlate with better design outcome, as do prototypes that have fewer parts added to them over the course of development. This paper also finds that committing more time to a project is not necessarily associated with a successful design outcome.

INTRODUCTION

The building of prototypes is an integral and important facet of the product design and development process. By building prototypes of design concepts, questions about a design or specific aspects of a design can be answered concretely. In other words, simulating a design through prototyping can reduce design risk without committing to the time and cost of full production [1]. Because of this, prototypes can be an effective way to compare design alternatives. Ward, et al [2] describe the advantages of building large numbers of prototypes to explore design alternatives before selecting a final design.

Prototypes are also a means to communicate an idea to others [3, 4]. A tangible, visual representation of a design concept is a shared view for all those involved in the design process.

This paper examines factors in prototyping, including part count and time spent on design and fabrication activity, and their correlations with design outcome over time. This work was done in the context of a mechanical engineering design course in which teams design and fabricate electro-mechanical devices.

The questions about prototypes this paper seeks to address are:

- In design, there is an adage: "Keep it simple." Do simpler design prototypes mean a more successful design outcome?
- Iteration and refinement are important elements in the design process. Does more prototyping lead to better designs?
- Does the amount of time spent on a project, both overall and on different activities over a project cycle, relate to design success?

RELATED WORK

Prototypes can range from simple 2-D sketches that represent design thinking [5-7] to foamcore mock-ups to sophisticated 3-D rapid prototyping designs that are nearly indistinguishable from a manufactured item. However, prototypes, by definition, are not production level design.

Ways of building prototypes

Prototypes in mechanical engineering are often thought of in terms of their *production technologies*. Rapid prototyping employs layered manufacturing to quickly build realistic physical prototypes. Virtual prototyping represents a design concept through detailed computer simulation. Many traditional methods of manufacture, such as machining, casting, and molding, are also employed in prototyping [8].

Purposes of prototypes

An alternative way of thinking about prototyping is in terms of the *purpose* of the prototype. Houde and Hill [1] posit that prototypes can serve three different purposes.

- One purpose is that of *function*, the ability of a proposed design to operate in a desired way. In the mechanical world, this is often known as a working prototype, and demonstrates that the essential functionality of a design operates as intended.

- A *look-and-feel* prototype is used to understand what the form and appearance of a design should be. An example is a non-functional industrial design model made of foam or rendered in 3-D.
- Finally, *role* prototypes give a sense of the usability of a design. Storyboards are often used to illustrate how and under what contexts a product might be employed by an end user.

A prototype often serves multiple purposes at once. For example, a prototype may be built as proof-of-concept for a technological function, and at the same time give a sense of role through the prototype's dimensions and weight. If the prototype is built to consider function, look-and-feel, and role together, then it is considered an *integration* prototype.

Stages of prototyping

Prototypes may also be considered by their *stage in development*. In software engineering, Sommerville [9] classifies prototypes as throwaway, evolutionary, or incremental. Throwaway prototypes are rough, early stage prototypes that help clarify requirements. An evolutionary prototype goes through iterative stages of building and evaluation. Incremental prototypes are modifications to existing products. Petroski [10] details the incremental path of several well known physical products. Budde, et al [11] describes a classification system similar to Sommerville, including evolutionary, experimental, and exploratory prototypes.

Fidelity of prototypes

A prototype may also be considered by its level of detail and realism, or *fidelity*. The building of prototypes is a trade-off between fidelity of the prototype and the resources required to produce the prototype, including time, effort, and cost. Ideally, designers should choose the "cheapest" prototype that is still effective, meaning a prototype that can be built quickly and inexpensively but still provide the information that the designer is looking for [12]. For example, a designer need not build a full working prototype when it is sufficient to construct a single mechanism to understand a design issue. Interface designers speak of mocking up throwaway "paper prototypes" that are quickly drawn sketches of software interfaces used to elicit user feedback [13].

The intent of a prototype (function, look-and-feel, or role) can be represented by any stage of development or level of fidelity. That is, a look-and-feel model may be a throwaway prototype, or it can be a highly faithful representation of a design.

Design correlations

This study is concerned with correlating factors in prototyping with design outcome. There is a growing body of research on correlating factors in the design process with design outcome. Mabogunje and Leifer [14] looked at the relationship between noun-phrases in design discourse and design outcome. Dong, et al [15] consider the role of coherency in team documentation in design outcome. Previous work by Yang [16] examined the role of sketching and design outcome. One of the findings was that dimensioned drawings appeared to be more significant in the design process than drawings that did not include dimensions. It was proposed that dimensioned drawings were important because they are more concrete than drawings without dimensions, and a step towards physical prototyping. It is from this observation about the importance of prototyping that this study is grows.

METHODS

Testbed

The testbed for this work is a mechanical engineering design course for juniors and seniors at the California Institute of Technology. This course includes twenty-three students divided into twelve teams of two. It should be noted that in these teams, each student is required to design, build and test his or her own device and these efforts will be graded independently of his or her teammates'. In this way, each student's work will be assessed individually and fairly.

Each participant builds their device using only elements from a kit containing a wide variety of materials, such as steel, aluminum, and plastic. Aside from motors and bearings, each participant fabricates virtually every component of his or her own device in the machine shop. A typical device is shown in Figure 1.

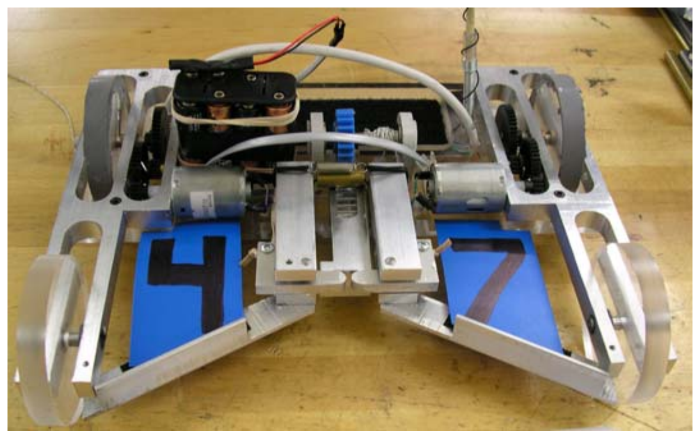

Figure 1 Example electromechanical design prototype

In this study, no assessment was made of the previous design experience of the participants. However, a survey of previous experience was made in this same course in an earlier year in [16]. In that study, students self-reported that they possessed above average experience and skills in engineering analysis, engineering intuition, engineering fabrication and arts-and-crafts. These students described themselves as below average in terms of experience and skills in drawing, tinkering, and construction. It was found that the only background or skills that significantly correlated with design outcome were engineering fabrication and engineering intuition.

At the beginning of the ten-week project, each team creates three illustrated scenarios of potential design alternatives along with a non-functional form mockup made of soft materials. The team then selects one conceptual direction to pursue in the four remaining milestones. In each of these milestones, teams present prototypes and sketches to show their progress. Prototypes are almost entirely constructed from kit materials. A schedule of these milestones in listed in Table 1. The final week, week 10, is marked by a popular, public contest in which the teams face against each other in a double elimination competition.

Milestone	*Week*	*Description*
1	4	Fabricate a key component or sub-assembly of the design
2	6	Present prototype with any additional components or sub-assemblies constructed since last milestone
3	9	Demonstrate the assembled, operational device
4	10	Device is fully functional and contest ready

Table 1 Schedule of project milestones

The work in this paper is based on assessments of the number of parts at each milestone. Each participant also kept a weekly track of time spent on activities including design, fabrication, debugging, and class attendance.

Design outcome

Design outcome may be considered in many ways. Device performance is an obvious measure of design outcome, but in this course, the functional performance metrics of devices are not pre-specified. This is in part because there are multiple possible design solutions to the problem, and the final contest conditions can change dramatically depending on the opponent a team comes up against. The final grade is a comprehensive metric that evaluates several aspects of design process. For the purposes of this study, final grade and contest performance were used as metrics for design outcome. The final contest measure is a ranking of the team's performance in competition. From the point of view of student designers, the goal is to design and build a functioning device that can compete in the contest. The students are constrained by time (deadlines) and by the materials available for prototyping in their kit.

The Spearman Ranking Correlation [17] for nonparametric populations was employed to test for correlations between design data and design outcome. The Spearman correlation coefficient R_s is computed in Equation 1:

$$R_s = 1 - \frac{6 \cdot \sum_{i=1}^{N} d_i^2}{N^3 - N} \qquad (1)$$

where N is the number of individuals and $d_i = X_i - Y_i$. X and Y are the ordinal rank of the variables being correlated, in this case design data and design outcome. R_s can take on a value between -1 and 1. If $-1 < R_s < 0$, there is a negative correlation between the two data sets. If $0 > R_s > 1$, there is a positive correlation. For a population N = 23, if the correlation coefficient R_s exceeds 0.353, it is considered statistically significant for a significance level, or a probability of error, of $\alpha = 0.05$.

RESULTS

In the classification of prototypes of [1], the intent of the milestone prototypes were found to be primarily *functional*. Most of these prototypes could be further categorized as *evolutionary* [9] because each one was an iterative version that builds on the previous one. However, levels of fidelity for prototypes vary widely. In terms of fit and finish, components were generally fabricated of "final" kit materials rather than throwaway materials such as foamcore or cardboard.

One measure relevant to prototyping is part count. This is the number of fabricated components in each prototype. Consider the correlation of number of parts with design outcome at each of the four milestones as shown in Table 2.

	Rs with Grade	*Rs with Contest*
Milestone 1*	-0.12	-0.13
Milestone 2	0.15	-0.39
Milestone 3	-0.21	-0.47
Milestone 4	-0.41	-0.51

Table 2 Correlation between number of parts and design outcome

Statistically significant negative correlations (highlighted) are seen with the last milestone and final grade, and with all but the first milestone and contest results. This negative correlation means that *fewer* overall number of parts in a device correlates with *better* grade and contest ranking for some milestones.

These milestones are meant to be snapshots of the evolution of each design prototype. However, a part count does not reveal how the parts are being added. Are new parts added at each milestone? Or are existing parts in a prototype being refashioned? Figure 2 illustrates the average number of individual parts found in each device at each milestone.

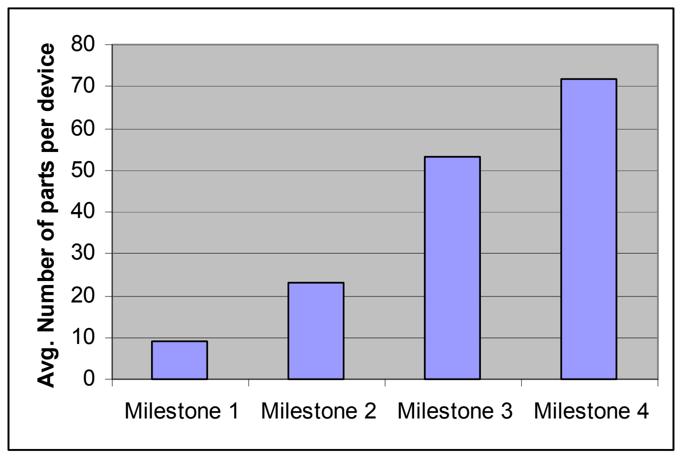

Figure 2 Average number of parts per device

Observe that the number of parts is always increasing. If there was a leveling out, or drop, in the number of parts, it could be inferred that design iteration (swapping out parts for others) or refinement (reducing the number of parts) was occurring. This steady rise in part count suggests that design and prototyping effort might be spent on incrementally building up or finishing a functional prototype. This is consistent with photographic records that suggest that new parts are being added incrementally.

Table 3 shows the change Δ in the number of parts from milestone to milestone correlated with design outcome measures.

[*] In cases marked with an *, data from one participant was unavailable, making N = 22 instead of 23. For such cases, the threshold value increases to $R_s = 0.361$

Change in number of parts	*Rs with Grade*	*Rs with Contest*
Δ Milestone 2 – 1*	0.19	-0.41
Δ Milestone 3 – 2	-0.29	-0.25
Δ Milestone 4 – 3	-0.40	-0.37
Δ Milestone 4 – 1*	-0.42	-0.56

Table 3 Correlation between change in number of parts and design outcome

There are negative, statistically significant correlations between the changes in number of parts between several milestones. Broadly, this means that the *fewer* number of parts *added*, the better the correlation with improved design outcome, particularly between the last milestone (which is the end of the project) and the second to last milestone, and between the last milestone and the first milestone. Coupled with the findings from Table 2, this suggests that a prototype that starts out with fewer components, and has fewer parts added to it is associated with a better design outcome.

Figure 3 shows the average number of hours spent per week on the project by each student, including design, fabrication, debugging, and class time. The overall pattern is for the amount of time on the project to increase steadily, perhaps echoing the increase in number of parts in Figure 2. The time spent designing is somewhat higher in the first few weeks, and then drops off towards the end of the term. Fabrication takes the lion's share of time and increases markedly towards the project, as does debugging/testing of the prototype. On average, 9% of each participant's time was spent in class, 22% on design, 32% on debugging, and 54% on fabrication. Note that weeks 9 and 10 are short weeks due to a holiday and the contest itself, and are accompanied by a drop in the amount of time spent.

In the context of design milestones, time spent designing drops off in Milestone 1 (week 4), presumably as students turn their focus on fabrication. By milestone 2 (week 6), there is a steady increase in prototyping efforts. By Milestone 3 and 4 (weeks 9 and 10), however, proportionately more time is spent debugging

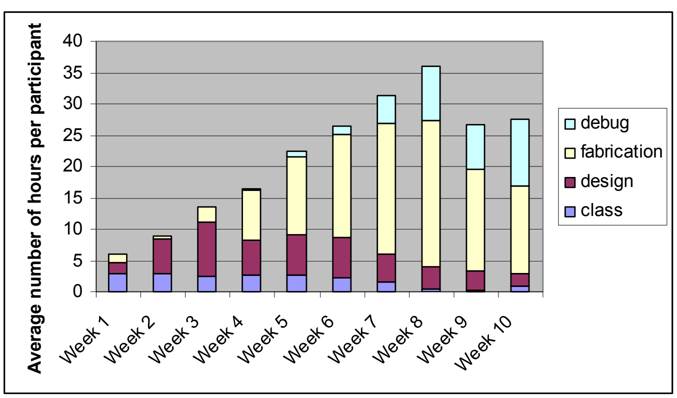

Figure 3 Average number of hours spent per participant per week broken down by activity

Table 4 lists how time spent on individual design-related activities over the life of the project correlates with design outcome.

*Activity**	*Rs with Grade*	*Rs with Contest*
Design	0.22	-0.10
Fabrication	-0.20	-0.59
Debugging/testing	0.38	-0.09
Total time	-0.17	-0.57

Table 4 Correlation between time spent on activities and design outcome

Of the three activities, time spent on testing is the only one that correlates in a statistically significant, positive way with final grade. This is not in itself unexpected, as a well tested device seems likely to result from a good design and fabrication process. One would also guess that such a device would perform better. The fact that design and fabrication are not significantly correlated, however, is surprising.

Time spent on fabrication and total time both correlate statistically significantly negatively with the contest. That is, spending *less* time on fabrication and prototyping, as well as less time overall correlates with better performance in the final contest.

Now consider the amount of time spent each week on all activities as a percentage of the total spent by each participant. This normalizes for the fact that some students may work at a different pace than others, and, more importantly, shows the effect of time spent at different points over the project cycle. This running percentage of time spent by week is shown in Table 5:

% of overall time*	*Rs with Grade*	*Rs with Contest*
Week 1	0.01	0.28
Week 2	0.06	0.35
Week 3	0.30	0.46
Week 4	0.36	0.51
Week 5	0.36	0.43
Week 6	0.23	0.40
Week 7	0.07	0.38
Week 8	0.09	0.36
Week 9	0.15	0.41

Table 5 Correlation between running percentage of time spent by each participant with final grade and contest

There is a positive, significant correlation between the percentage of time spent on a project and contest result from week 3 until the end of the project. That is, the higher the percentage of total time spent in these weeks, the better the contest results. Because this is a running total, this implies that a designer who spends a critical amount of time by the third week and continues to do so for the remainder of the project will correlate with a better contest result. It is also apparent that the percentage of overall time spent in weeks 4 and 5 are linked to final grade, and that the more time spent by those weeks as a percentage of overall time is associated with better grades.

DISCUSSION & CONCLUSIONS

This study examined the role of prototyping in design by observing part count and time spent on various activities during the design and development cycle. Consider the answers to the questions posed in the introduction in light of the findings of this study:

- *Do simpler prototypes mean a more successful design?*

Statistically significant negative correlations were observed between the last milestone and final grade, and with all but the first milestone and contest results. This negative correlation means that *fewer* overall number of parts in a device correlates with *better* grade and contest ranking for some milestones.

Simplicity is a common goal in design, and one measure of this is part count at each milestone. Intuitively, having fewer parts means less to design, fabricate, test, assemble, and maintain. Not surprisingly, one of the key guidelines in Design for Assembly methodology [15] is the minimization of part count.

It is interesting to consider the relationship of simplicity to design quality. Often, very simple products are considered the more elegant and better thought out. In this project, it was observed that the basic functionality of many of the designs that resulted from this course were very similar. Most teams settled on a 3- or 4- wheeled car that would work in tandem with a stationary winch. This general class of solution was judged by the teaching staff to have low risk of failure with a high probability of success in the contest. It should be noted that this part count was tracked at milestones, but whether each milestone's parts were incrementally added was not tracked (although in several cases, the incremental increase was anecdotally true). In general, however, informal observation of the teams showed that the simpler of devices generally did better than others. Design quality was not explicitly used as a design outcome (nor is it an easy measure to arrive at), but it could be a useful study to see if there is a relationship between it and design simplicity.

- *Does more prototyping lead to better designs?*

This study shows an association between designs that limit the number of parts added over time and design outcome. A steady increase in parts over time for most designers implies that part fabrication was likely for new components. However, this study did not log what percentage of parts at each milestone could be considered "new" rather than revised, that is, whether parts were being added to an existing prototype, or new prototypes were being created in their entirety at each milestone. However, it is assumed that the former is much more likely, and further infer that the more successful designers who added comparably fewer parts focused more on *refining* and *testing* their existing prototypes rather than adding on a large number of new components.

It should be noted that this study did not track exactly how parts were incorporated into a prototype, in particular whether an individual new part was a new addition to a design or simply a revision of an existing part. Such an observation would provide better insight into the nature of iteration in design. One of the challenges of such a study would be determining what constitutes an iteration of a design. Is it simply the addition or revision of a part? Or is there some threshold of change that has to be met before it can be considered a change, as in successive product releases. And at a lower level, at what granularity can one measure a design change in a part?

This study also considers the quantity of prototyping by the amount of time spent on it as an activity. The percentage of time spent by the teams on fabrication was greater than the other three activities combined. However, fabrication time did not correlate with final grade, and in fact had a statistically significant negative correlation with contest result. The *less* time spent building a design, the *better* the ranking in the final design contest. While this may be counterintuitive, it is consistent with the finding that simpler designs comprised of fewer parts were associated with more successful design outcomes. Having fewer parts in a design implies that less time will be spent on all phases of the design cycle.

- *Does the amount of time spent on a project, both overall and on different activities over a project cycle, relate to design success?*

Time is a critical, limited resource on any design project, and on the face of it, it would make sense that spending more time on a project would lead to a better design result. This belief was supported in looking at the time spent debugging and its correlation with final grade. More time spent debugging a design suggests that a prototype will function more reliably or consistently. However, this work finds that spending *less* time on fabricating a prototype was correlated with better contest results as discussed above.

In this study, the overall quantity of time spent on all activities in the project correlated negatively with contest performance. Again, this is somewhat counterintuitive, but it may be appropriate to explain this result by referring back to the earlier findings about simplicity. Simpler prototypes are linked with better design outcomes, and it might be reasonable to assume that such designs would require less time to design, build, and test. This finding also suggests that merely "putting in the time" is not sufficient for design success, but that it is related to having the foresight to come up with a manageable design scope.

It was found that the proportion of overall time spent on the project, week-by-week on all activities had a significant correlation with contest results. This result implies that designers who meet a threshold level of time commitment (as a percentage of their overall time) and maintain that commitment are somehow linked to doing better. A participant who "slacks off" for the first half of the project is unlikely to catch up later on.

The amount of time spent on a project is important, but committing raw hours in itself is not associated with success. This study shows correlations that suggest that it is more useful to spend time consistently, and to put forth efforts on a well scoped design.

It is interesting to note that above factors differ in the way they correlate with contest and grade. At first glance, one would think they would produce similar results, but they are very different measures. Grades are somewhat subjective in nature, particularly in this type of design course, because they take into consideration the design process of the individual participant. A contest is not cumulative in nature, and factors that do not matter in the final grade become important. For example, the ability to control one's device with a joystick is critical in competition, and the ability for one's device to last through several rounds of competition without breaking is also necessary to rank well.

Future work in prototyping will include further examining the role of prototype generation as a method for concept selection [2], and characterizing the value of iteration in prototyping.

ACKNOWLEDGMENTS

The author gratefully acknowledges the support and guidance of the instructors of the course, Prof. Erik Antonsson, Prof. Joel Burdick, and Dr. Curtis Collins at the California Institute of Technology, and the commendable design efforts of the students that are the basis of this research. The author also acknowledges the generous sponsors of the course: Applied Materials, Amerigon, Dr. David & Mrs. Barbara Groce, Honeywell, idealab!, Mabuchi Motor, Northrop Grumman, The San Diego Foundation, and Toro.

REFERENCES

1. Houde, S. and C. Hill, *What do Prototypes Prototype?*, in *Handbook of Human-Computer Interaction*, M. Helander, T. Landauer, and P. Prabhu, Editors. 1997, Elsevier Science: Amsterdam.
2. Ward, A., et al., *The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster.* Sloan Management Review, 1995. **36**(3): p. 43-61.
3. Schrage, M. and T. Peters, *Serious Play: How the World's Best Companies Simulate to Innovate*. 1999, Boston, MA: Harvard Business School Press.
4. Kolodner, J.L. and L.M. Wills, *Powers of observation in creative design.* Design Studies, 1996. **17**(4): p. 385-416.
5. Ullman, D.G., S. Wood, and D. Craig, *The Importance of Drawing in the Mechanical Design Process.* Computers & Graphics, 1990. **14**(2): p. 263-274.
6. Goel, V., *Sketches of thought*. 1995, Cambridge, Mass.: MIT Press. xv, 279.
7. Suwa, M. and B. Tversky, *What Do Architects and Students Perceive in their Design Sketches? A Protocol Analysis.* Design Studies, 1997. **18**(4): p. 385-403.
8. Kiefer, S., L. Silverberg, and M. Gonzalez, *A case study of prototyping methods and design for manufacture: electrostatic window blinds.* Journal of Engineering Design, 2004. **15**(1): p. 91 - 106.
9. Sommerville, I., *Software Engineering*. Fifth ed. 1995: Addison-Wesley.
10. Petroski, H., *Invention by Design: How Engineers Get From Thought to Thing*. 1996, Cambridge, Mass.: Harvard University Press.
11. Budde, R., K. Kautz, and K. Kuhlenkamp, *Prototyping: An Approach to Evolutionary System Development*. 1992, Berlin: Springer.
12. Dijk, L., J.S.M. Vergeest, and I. Horváth, *Testing shape manipulation tools using abstract prototypes.* Design Studies, 1998. **19**(2): p. 187-201.
13. Wagner, A., *Prototyping: A Day in the Life of an Interface Designer*, in *The Art of Human Computer Interface Design*, B. Laurel, Editor. 1990, Addison-Wesley: New York. p. 79-84.
14. Mabogunje, A. and L. Leifer. *210-NP: Measuring the Mechanical Engineering Design Process*. in *Twenty-Sixth Annual Frontiers in Education Conference on Technology-Based Re-Engineering Engineering Education*. 1996. Salt Lake City, UT.
15. Dong, A., A.W. Hill, and A.M. Agogino, *A Document Analysis Method for Characterizing Team-Based Design Outcomes.* Journal of Mechanical Design (in press), 2004.
16. Yang, M.C. *Concept Generation and Sketching: Correlations with Design Outcome*. in *2003 ASME Design Engineering Technical Conferences*. 2003. Chicago, IL: ASME.
17. Siegel, S., *Nonparametric Statistics for the Behavioral Sciences*. McGraw-Hill Series in Psychology, ed. C.T. Morgan. 1956, New York, NY: McGraw-Hill. 312.
18. Kuffner, T.A. and D.G. Ullman, *The information requests of mechanical design engineers.* Design Studies, 1991. **12**(1): p. 42-50.
19. Baya, V. and L.J. Leifer. *A Study of the Information Handling Behavior of Designers During Conceptual Design*. in *Sixth International Conference on Design Theory and Methodology*. 1994. Minneapolis, MN: American Society of Mechanical Engineers.