

A study of prototypes, design activity, and design outcome

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The building of prototypes is an important facet of the product design process. This paper examines factors in prototyping, including part count and time spent on various design activities, and their correlations with design outcome. The research questions asked: Do simpler prototypes mean a more successful design? Does the amount of time spent on a project, both overall and on different activities over a project cycle, relate to design success? And does it matter when this time is spent? 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.
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The building of prototypes is an important facet of the product design and development process. Simulating a design through prototyping can reduce design risk without committing to the time and cost of full production (Houde and Hill, 1997). By building prototypes of design concepts, questions about a design or specific aspects of a design can be answered concretely. Will a material be sufficiently stiff? Will a design configuration perform as expected? Furthermore, prototypes can be an effective way to compare design alternatives and aid in concept selection. Ward et al. (1995) describe the practice of building large numbers of prototypes to explore design alternatives before selecting a final design. This is contrary to common design wisdom that calls for deep exploration in the conceptual stage, before fabrication.

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Prototypes are also a means to communicate an idea to others (Kolodner and Wills, 1996; Schrage and Peters, 1999). A tangible,



visual representation of a design concept is a shared view for all involved in the design process. In addition, the *process* of constructing and refining a 3-D physical prototype can bring up design issues in ways that alternative representations often cannot. While the process of developing of a 2-D drawing or even a computer generated solid model can generate a great deal of information about a design, that information will likely be different than that gained by physically cutting metal, for example.

This paper examines factors in prototyping, including part count and time spent on design and fabrication activity, and their correlations with design outcome. This work was done in the context of a mechanical engineering course in which teams designed and fabricated electro-mechanical devices, and is based on preliminary research presented earlier by the author (Yang, 2004).

Questions about prototypes this paper explores:

- In design, there is an adage: ‘Keep it simple’. Do simpler design prototypes mean a more successful design outcome?
- Does the amount of time spent on a project, both overall, and on design and prototyping activities over a project cycle, relate to design success?
- Is the timing of activities in the design cycle associated with certain design outcomes?

1 Related work

A prototype is an early embodiment of a design concept. Prototypes can range from simple 2-D sketches that represent design thinking (Ullman et al., 1990; Goel, 1995; Suwa and Tversky, 1997) to foamcore mock-ups to sophisticated 3-D rapid prototyping designs that are nearly indistinguishable from a manufactured item. By definition, prototypes are not production stage design.

1.1 Ways of building prototypes

Prototypes in mechanical engineering are often thought of in terms of their *production technologies*. Many traditional methods of manufacture, such as machining, casting, and molding, are employed in prototyping (Kiefer et al., 2004). Rapid prototyping employs layered manufacturing to quickly build realistic physical prototypes. Virtual prototyping represents a design concept through detailed computer simulation.

1.2 Prototyping as a design language

There is a substantial body of work that describes how sketching is a design ‘language’, a way to express design thinking (Ullman et al., 1990; Suwa and Tversky, 1997; Cross, 1999). The building of 3-D prototypes may also be thought of as a type of design language in the sense that it represents and embodies design thought. However, the creation of prototypes requires a set of design skills and time commitment that are a level removed from hand sketching. Little overhead is required for the proverbial cocktail napkin drawing of an idea, but more resources are needed to construct something in 3D, even out of simple materials.

1.3 Purposes of prototypes

Prototypes can be thought of in terms of their *purpose*, or the categories of questions they answer about a design. Ullman (2003) describes four classes of prototypes based on their function and stage in product development:

- To better understand what approach to take in designing a product, a *proof-of-concept* prototype is used in the initial stages of design.
- Later, a *proof-of-product* prototype clarifies a design’s physical embodiment and production feasibility.
- A *proof-of-process* prototype shows that the production methods and materials can successfully result in the desired product.
- Finally, a *proof-of-production* prototype demonstrates that the complete manufacturing process is effective.

Houde and Hill (1997) propose a triangle model of early stage proof-of-concept prototypes as shown in Figure 1.

Each corner of the triangle represents a different purpose for a prototype:

- To understand a design’s *function*, the ability of a proposed design to operate in a desired way. In the mechanical world, a working prototype demonstrates the essential functionality of a design.

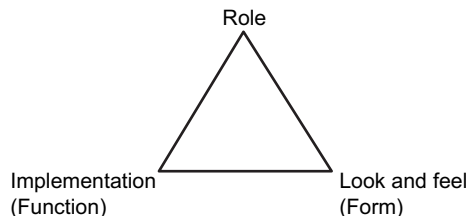


Figure 1 What prototypes prototype (Houde and Hill, 1997)

- A *look-and-feel* prototype represents the form and appearance of a design. An example is a non-functional industrial design model made of foam or rendered in a 3-D model (Ferguson, 1992).
- 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, moving along points in the triangle. For example, a prototype may be a proof-of-concept for functional performance, 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.

1.4 Stages of prototyping

Prototypes may also be characterized by their *stage in development*. In software engineering, Sommerville (1995) 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 (1996) details the incremental path of several well known physical products. Budde et al. (1992) describe a classification system similar to Sommerville, including evolutionary, experimental, and exploratory prototypes.

1.5 Fidelity of prototypes

A prototype may be considered by its level of realism, or *fidelity*. The building of prototypes is often a trade-off between fidelity and the time, effort, and cost required to produce that prototype. 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 (Dijk et al., 1998). For example, a designer need not machine a complete working prototype out of aluminum when it is sufficient to quickly construct a single mechanism out of foamcore to understand a configuration issue. Suppose a design team wants to explore various design alternatives for a software interface. Interface designers speak of 'mocking up' 'paper prototypes' that are simple hand-sketches of software interfaces used to elicit valuable user feedback (Wagner, 1990). Rather than investing in writing a fully functional software program, effort is spent only on the interface design issues at hand. Likewise, product designers use minimally functional 3D prototypes for usability testing.

Each of the classifications above can be used to describe prototypes. 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.

1.6 Design correlations

This study is further 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 \(1996\)](#) looked at the relationship between noun-phrases in design documentation and design outcome. [Dong et al. \(2004\)](#) consider the role of coherency in team documentation in design outcome. Previous work by [Song and Agogino \(2004\)](#) and [Yang \(2003\)](#) examined sketching and design outcome. One of the findings by Yang was that dimensioned drawings appeared to be more significant than drawings that do not include dimensions. It was proposed that dimensioned drawings were important because they are more concrete than drawings without dimensions, and a step closer to physical prototyping. It is from this observation about the value of prototyping that this study grows.

2 Methods

2.1 Testbed

This study examines the work produced in an advanced mechanical engineering design course for juniors and seniors at the California Institute of Technology in the Fall of 2002 ('Class 1') and again with a different set of students in the Fall of 2003 ('Class 2'). Each course includes 23 students divided into 12 teams of two (one team consisted of a student and a teaching assistant). In these teams, each student is required to design, build and test his or her own standalone device to compete in a final design contest. Although teammates are encouraged to discuss ideas together and will compete in tandem, each device is graded independently so that they may be assessed fairly. Each class is assigned its own unique design challenge. In Class 1, each team's devices start on either side of a large circular table, then must remove an aluminum flag from their side, transport it to their opponents' side, and plant the flag there. In Class 2, each team starts inside a large aluminum cage placed on the centerline of a table. Each team must move the cage to their opponents' side of the centerline by the end of the allotted time.

The classes were identical in terms of resources available to the teams and course materials. However, the abilities of a class may change from

year to year. One comparison point is the average grade of each class. The average number of final points in Class 1 was 88.9 out of a possible 100 points with a standard deviation of 8.4. In Class 2, the average number of points was 83.0 with a standard deviation of 5.8. These averages suggest that Class 1 may consist of slightly better performers than Class 2.

Each participant builds his or her device using only elements from a kit containing a wide variety of parts and materials, such as steel, aluminum, and plastic sheet. Aside from motors, bearings, and gears, each participant fabricates virtually every component of his or her own device in the machine shop, including transmission and wheels. A typical device is shown in [Figure 2](#).

Students in both Class 1 and Class 2 had taken a required introductory course in engineering design that presented basic design methodologies and machine shop skills such as milling and turning. In a survey of the previous design experience of the participants in Class 1 ([Yang, 2003](#)), it was found that previous self-reported engineering fabrication skill correlated statistically significantly positively with final grade. It makes sense that engineering fabrication skill is critical in the type of hands-on design projects that are the focus of this study, and it is possible that prototyping ability outweighs other skills or processes that are taught to students as factors in design outcome. However, engineering intuition as self-reported on a five point scale correlated statistically significantly negatively with contest result. It is somewhat surprising that students who thought they possessed better engineering intuition did more poorly than students who did not. These findings may be an effect of having novice engineers assess their own abilities.

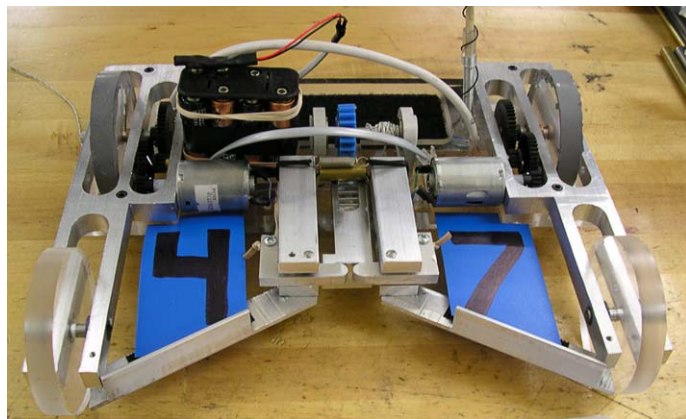


Figure 2 Example electro-mechanical design prototype

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

The work in this paper is based on assessments of the number of parts at each milestone as well as time spent on the activities in design. Each participant maintained a log of time spent each week on design, fabrication, debugging, and class attendance. Students were informed that the hours tracked were for record keeping purposes only, and would not be taken into account for grading.

2.2 Design outcome

The success of a design 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 faces. For the purposes of this study, final grade and contest performance were used as metrics for design outcome. The final grade in the course is a cumulative measure that evaluates both the design process used to achieve the design and the design itself. The measure of design process includes assignments that develop project objectives, requirements and functions, three initial design alternatives, a non-functional 3-D mockup of the selected approach, and assessment of each students' logbook. The device design itself is judged at four milestones, and criteria considered include the overall concept, the details of the design, the fabrication of the device, and the planning involved in the device.

Table 1 Schedule of project milestones (Class 1 and Class 2)

Milestone	Week	Description
1	4	Fabricate a key component or sub-assembly of the design
2	6	Present prototype with 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

The final contest ranks a team's performance in competition. Note that contest performance and grade are independent of each other. A student can earn a good grade based on his or her performance in the course assignments, but do poorly in the contest, and vice versa. The main constraints that students face are time necessary for design, fabrication, and debugging, and by the materials available for prototyping in their kit.

The Spearman Ranking Correlation (Siegel, 1956) for nonparametric populations was employed to test for correlations between design data and design outcome. The Spearman correlation coefficient R_s is computed in Eq. (1):

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

where N is the number of individuals and $d_i = X_i - Y_i$. X and Y are the ordinal ranks 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 example, in a population of college students who have taken introductory and advanced versions of a course, it might be expected that the student ranking in the introductory course will correlate somewhat with the ranking in the advanced. If the top student by rank in the introductory course (X_1) is the fourth ranked student in the advanced course (Y_1), and that the difference $d_1 = 1 - 4 = -3$. In these classes, $N = 23$, and if the correlation coefficient R_s exceeds 0.415 , it is considered *statistically significant* for a significance level, or a probability of error, of $\alpha = 0.05$ (two tailed).

3 Results and discussion

3.1 Prototypes

The following results for prototypes are from Class 2 only. No data on part count was kept for Class 1 because the study of prototypes in Class 2 in fact grew out of preliminary research on sketching in Class 1. These prototypes could all be described as proof-of-concepts, using Ullman's (2003) categorizations. Prototypes were fabricated using material removal methods (milling and turning) on metals and plastics and polymer casting. Applying the classification scheme for prototypes of Houde and Hill (1997), the intent of the prototypes was found to be primarily *functional*. Prototypes presented at each milestone were

constructed to see if they would operate as intended. Appearance and usability were secondary considerations. Prototypes could be further categorized as *evolutionary* (Sommerville, 1995) because generally each was an iteration of the previous one. Components in the prototypes were generally fabricated of ‘final’ kit materials rather than temporary soft materials. Because these prototypes would be likely used in the final device, the *level of fidelity* of the prototypes is considered to be high. As expected with realistic prototypes, the resources required to produce these parts were also high.

An important element of prototyping is the learning that the designer acquires during fabrication. In lecture, students were encouraged to pose questions about their designs and then answer these questions through building. This is closely related to the traditional design–build–test cycle of design. In their logbooks, students asked questions that ranged from the general (‘Will my idea work?’) to the specific (‘Will 1/8” plastic make a strong enough chassis?’). It was observed that students soon discovered that answering their questions through building prototypes would lead to other questions that could not have been considered before (‘1/8” plastic is strong enough for a chassis, but the part I made shows that cracks form where holes are drilled close to each other.’). In effect, prototyping *was* learning.

One measure relevant to prototyping is part count. This is the number of components in each prototype presented at each milestone, not including manufactured components such as motors and screws. Figure 3 lists the average number of individual parts found in each device at each milestone.

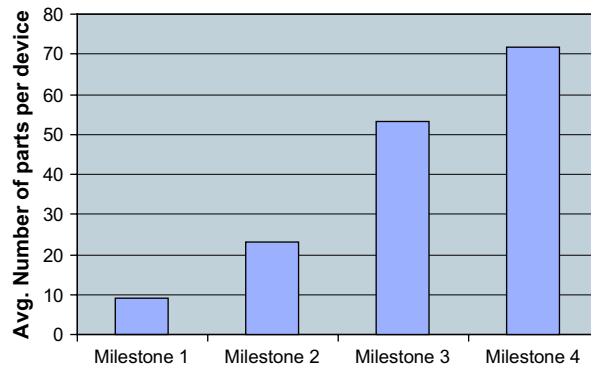


Figure 3 Average number of parts per device (Class 2 only)

Notice 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 is spent on incrementally building up a prototype. This is consistent with photographic records that suggest that new parts are being added incrementally.

Table 2 shows the correlation of number of parts with design outcome at each of the milestones.

Statistically significant negative correlations (values in italic) are seen with the last milestone and final grade, and with the third and fourth milestones and contest results. This negative correlation means that *fewer* overall number of parts in the final device correlates with *better* grade and contest ranking. In both contest and grade, the correlation tends to increase *negatively* with time.

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

This correlation is statistically significant between the last milestone at the end of the project for both grade and contest ranking. Broadly, this suggests that the *fewer* number of parts *added*, the better the correlation with improved design outcome. Coupled with the findings from Table 2, this suggests that a prototype that not only starts out with fewer components, but has fewer parts added to it is associated with a better design outcome.

3.1.1 Levels of integration

Common design wisdom holds that integration of design prototypes early on will lead to a better prototype in the end. By assembling components and sub-assemblies ahead of time, the literal nuts-and-bolts

Table 2 Correlation between number of parts and design outcome (Class 2 only)

Milestone	R_s with grade	R_s with contest
1 ^a	-0.12	-0.13
2	0.15	-0.39
3	-0.21	-0.47
4	-0.41	-0.51

For $N = 23$, $R_s > 0.415$ is considered statistically significant for $\alpha = 0.05$ (two tailed).

^a In these cases, data from one participant was unavailable, making $N = 22$ instead of 23. For such cases, the threshold value increases to $R_s = 0.425$ for $\alpha = 0.05$ (two tailed).

Table 3 Correlation between change in number of parts and design outcome (Class 2 only)

Change in number of parts	R_s with grade	R_s with contest
Δ Milestone 2–1 ^a	0.19	–0.41
Δ Milestone 3–2	–0.29	–0.25
Δ Milestone 4–3	–0.40	–0.37
Δ Milestone 4–1 ^a	–0.42	–0.56

For $N = 23$, $R_s > 0.415$ is considered statistically significant for $\alpha = 0.05$ (two tailed).

^a In these cases, data from one participant was unavailable, making $N = 22$ instead of 23. For such cases, the threshold value increases to $R_s = 0.425$ for $\alpha = 0.05$ (two tailed).

issues associated with prototype integration are worked out over time rather than all at once at the end of a project. One measure of how quickly integration takes place is the ratio of assembled parts at each milestone to the number of assembled parts in the final prototype (Milestone 4). Parts that have been fabricated but not yet assembled are not included in this count. Table 4 shows that this ratio generally increases with each successive milestone.

Table 5 shows the correlation of these ratios with grade and contest ranking.

There is a statistically significant correlation between the ratio of assembled parts in Milestone 2 and Milestone 4 with grade. Milestone 1 (week 4) is the first review in which students must present a piece of hardware fabricated from kit materials. By Milestone 2 (week 6), the prototypes are expected to have some degree of functionality, and it would make sense that by this point students should have made significant progress towards their final design. However, there are no statistically significant correlations with the ratio of Milestones 3 to 4, which may be in part because by that stage of the project, more students have integrated their components, and the ratio is less of a differentiator between teams.

Table 4 Ratio of assembled parts at each milestone to the final number of assembled parts (Class 2 only)

	Average ratio
Milestone 1/Milestone 4	0.11
Milestone 2/Milestone 4	0.28
Milestone 3/Milestone 4	0.77
Milestone 4/Milestone 4	1.00

Table 5 Correlation between ratio of assembled parts at each milestone to the final number of assembled parts (Class 2 only)

	R_s with grade	R_s with contest
Milestone 1/Milestone 4 ^a	0.18	-0.16
Milestone 2/Milestone 4	0.49	0.03
Milestone 3/Milestone 4	0.38	0.19

For $N = 23$, $R_s > 0.415$ is considered statistically significant for $\alpha = 0.05$ (two tailed).

^a In these cases, data from one participant was unavailable, making $N = 22$ instead of 23. For such cases, the threshold value increases to $R_s = 0.425$ for $\alpha = 0.05$ (two tailed).

3.2 Time

We now consider the role of time spent on design and development activities. These results are for both Class 1 and Class 2. Table 6 shows the average number of hours spent in four project-related activities over one semester, including design, fabrication, debugging, and class time, along with the percentage of total time spent on each activity.

- *Design* is concerned with conceptual design including configuration layout and component design.
- *Fabrication* relates to effort spent constructing and assembling the device. This is usually closely linked to the amount of time spent by the student designer in the machine shop.
- *Debugging* focuses on testing the device to assess performance.
- *Class* is time spent in the classroom.

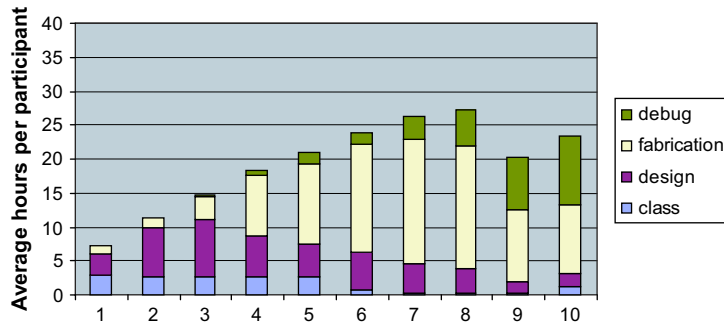
The difference in total time between Class 1 and Class 2 is about 9%, most of which can be attributed to more fabrication time for Class 2.

Figures 4 and 5 show the average number of hours spent *per week* on each activity for both classes. The overall pattern is for the amount of time on the project to increase steadily. A subtle difference is seen in Class 1 where the increase in time spent over the first 8 weeks of class is

Table 6 Average time spent on activities and as a percentage of total time

Activity	Class 1		Class 2	
	Average hours	% Total	Average hours	% Total
Design	46	24	47	22
Fabrication	100	52	113	54
Debugging	31	16	32	15
Class	16	8	19	9
Total	193	100	211	100

Figure 4 Average number of hours spent per participant per week by activity (Class 1)



more gradual than in Class 2, meaning that more time spent early on (as a percentage) than in Class 1. Time spent designing drops off in Milestone 1 (week 4), presumably as students turn their focus on fabrication. This is one connection between drawing and prototyping. ‘Design time’ includes drawing, sketching, and planning. After ideas are solidified in students’ sketchbooks in two dimensions, the students move to the machine shop (‘fabrication time’) to implement the ideas in 3D. By Milestone 2 (week 6), there is a steady increase in prototyping efforts. By Milestones 3 and 4 (weeks 9 and 10), however, proportionately more time is spent debugging the prototype. 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.

Table 7 lists how time spent on individual design-related activities over the life of the project correlate with design outcome. For Class 2, Table 7 shows two statistically significant negative correlations between total time spent over the term on fabrication and contest performance, and total time spent on the course over the term and contest. That is, spending *less* time on fabrication, as well as less time overall correlates with better performance in the final contest. In the previous year’s

Figure 5 Average number of hours spent per participant per week by activity (Class 2)

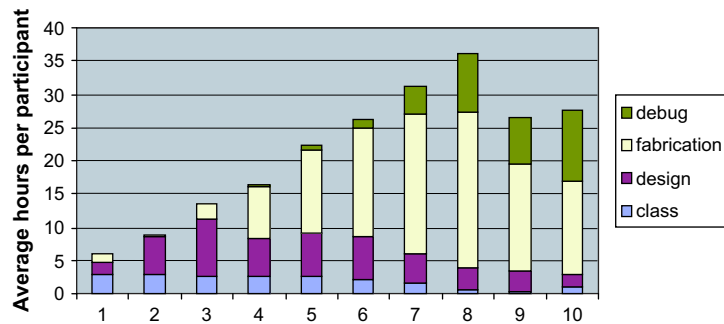


Table 7 Correlation between time spent on activities and design outcome (Classes 1 and 2)

Activity ^a	Class 1		Class 2	
	R_s with grade	R_s with contest	R_s with grade	R_s with contest
Design	0.34	-0.24	0.22	-0.10
Fabrication	0.08	0.01	-0.20	-0.59
Debugging	0.27	0.24	0.38	-0.09
Total time	0.14	-0.12	-0.17	-0.57

^a In these cases, data from one participant was unavailable, making $N = 22$ instead of 23. For such cases, the threshold value increases to $R_s = 0.425$ for $\alpha = 0.05$ (two tailed).

course, no correlation is found with any of the activities and either grade or contest performance. This may be in part because less time was spent overall in Class 1 than in Class 2, and the time was spent earlier on.

It is also useful to understand how time spent weekly on various activities correlates with outcome, as shown in Table 8 (Class 1) and Table 9 (Class 2).

- *Design.* In both Class 1 (in week 2) and Class 2 (in week 3), there is a statistically significant, positive correlation with time spent on design and grade. This is consistent with the findings implied by Yang (2003). That is, time spent sketching dimensioned drawings early on can correlate with better design outcome. Class 1 further shows a statistically significant negative correlation in week 7 with contest, meaning that time spent on design later in the project does not correlate well with contest performance.

Table 8 Design, fabrication, debugging, and total time spent per week correlated with grade and contest, by week (Class 1 only)

	Design time		Fabrication time		Debugging time		Total time	
	Grade	Contest	Grade	Contest	Grade	Contest	Grade	Contest
Week 1	0.22	0.32	0.39	0.11	0.19	0.29	0.41	0.32
Week 2	0.44	0.25	-0.11	0.25	0.31	-0.23	0.44	0.17
Week 3	-0.02	-0.08	0.27	0.50	0.03	0.32	0.11	0.29
Week 4	0.11	-0.32	0.50	0.45	0.26	0.26	0.38	0.15
Week 5	0.23	-0.42	0.00	0.21	0.30	0.28	0.20	0.01
Week 6	0.26	-0.23	0.05	0.14	0.36	0.17	0.20	-0.08
Week 7	0.35	-0.52	0.11	0.08	0.30	0.14	0.05	-0.17
Week 8	0.31	-0.34	-0.04	-0.08	0.37	0.36	0.14	-0.12
Week 9	-0.06	-0.32	-0.05	-0.27	-0.03	0.10	-0.34	-0.35
Week 10	-0.09	-0.24	0.00	-0.11	0.07	0.12	0.16	-0.07

For $N = 22$, $R_s = 0.425$ for $\alpha = 0.05$, (two-tailed test).

Table 9 Design, fabrication, debugging, and total time spent per week correlated with grade and contest, by week (Class 2 only)

	Design time		Fabrication time		Debugging time		Total time	
	Grade	Contest	Grade	Contest	Grade	Contest	Grade	Contest
Week 1	-0.21	-0.11	-0.09	-0.29	-	-	-0.19	-0.30
Week 2	-0.14	-0.25	-0.10	-0.42	-	-	-0.16	-0.30
Week 3	0.43	0.20	-0.05	-0.60	-	-	0.35	-0.11
Week 4	0.24	0.19	0.09	-0.48	0.40	-0.01	0.21	-0.37
Week 5	0.20	-0.05	-0.10	-0.21	0.22	-0.34	0.08	-0.33
Week 6	0.33	-0.18	-0.64	-0.43	-0.13	-0.58	-0.41	-0.59
Week 7	-0.04	-0.31	-0.02	-0.08	-0.01	-0.62	-0.19	-0.41
Week 8	0.27	-0.15	-0.03	-0.40	0.26	-0.15	-0.08	-0.55
Week 9	0.09	-0.19	-0.25	-0.53	0.32	0.23	-0.07	-0.56
Week 10	0.00	-0.38	-0.18	-0.56	0.13	0.03	-0.24	-0.55

For $N = 22$, $R_s = 0.425$ for $\alpha = 0.05$, (two-tailed test).

- Fabrication.* In Class 1, there are positive, statistically significant correlations with fabrication time and design outcome in weeks 3 and 4 that suggest that time spent on building early on correlates well with design outcome. Furthermore, the level of correlation generally declines over time. In contrast, Class 2 has negative, statistically significant correlations with fabrication time and design outcome in weeks 3, 4, 6, 9, and 10, and the level of correlation does not have a clear trend over time. Interestingly, Class 2 spent more time on fabrication overall than Class 1. Possible reasons that the pattern of correlation differed for the two classes could be that Class 1 worked more efficiently than Class 2, or that they possessed more fabrication skills. Clearly, this is an avenue for further study.
- Debugging.* No correlations were found with time spent debugging and outcome for Class 1. Class 2 shows a negative, statistically significant correlation in weeks 6 and 7 with contest performance, meaning the more time spent on debugging a project correlates with poorer contest ranking. One possible reason for this is that, as a percentage of overall time, those in Class 2 spent more time later on debugging, rather than earlier as Class 1 had. Note that in weeks 1–3, none of the participants spent any time debugging so no correlation coefficient could be computed.
- Total.* A positive, statistically significant correlation is found between week 3 and design grade for Class 1. Class 2 shows a series of negative, statistically significant correlations with contest in the second half of the project cycle. As with the results for fabrication time (above), the Class 1 and 2 results may actually be thought of as consistent because they suggest that overall time spent early on correlates well, but time spent later on does not correlate well.

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 10.

In Table 10, Class 1 shows a positive, significant correlation between the percentage of time spent on the project in weeks 7 and 8 and with design grade. For Class 2, there is a positive, significant correlation between the percentage of time spent on a project and contest results from week 3 through 5. 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 in Class 2 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. For Class 1, this time frame is shifted down to week 7. This shift may be partially attributed to the amount of time spent earlier on in Class 1.

4 Conclusions

We now consider the answers to the questions posed in the introduction in light of the findings of this study.

4.1 Do simpler prototypes mean a more successful design?

The findings in this study suggest that *fewer* overall number of parts in a device correlate with *better* grade and contest ranking for some

Table 10 Correlation between running percentage of time spent by each participant with final grade and contest (Class 1 and Class 2)

% of overall time ^a	Class 1		Class 2	
	R_s with grade	R_s with contest	R_s with grade	R_s with contest
Week 1	0.19	0.30	0.01	0.28
Week 2	0.25	0.27	0.06	0.35
Week 3	0.11	0.37	0.30	0.46
Week 4	0.18	0.36	0.36	0.51
Week 5	0.21	0.28	0.36	0.43
Week 6	0.32	0.26	0.23	0.40
Week 7	0.43	0.20	0.07	0.38
Week 8	0.56	0.32	0.09	0.36
Week 9	0.19	0.10	0.15	0.41

For $N = 22$, $R_s = 0.425$ for $\alpha = 0.05$, (two-tailed test).

^a In these cases, data from one participant was unavailable, making $N = 22$ instead of 23. For such cases, the threshold value increases to $R_s = 0.425$ for $\alpha = 0.05$ (two tailed).

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, assemble, debug, and maintain.

Consider the relationship of simplicity to design quality. Often, very simple products are thought of as more elegant and better thought out than more complicated ones. In fact in these projects, it was observed that the basic designs were often very similar. In both classes, many teams settled on at least one 3- or 4- wheeled car that included a custom attachment for the particular design challenge, such as a winch or a pair of grippers. This class of solutions was judged by the teaching staff to have low risk of failure with a reasonable probability of success in the contest, and was considered relatively straightforward to design and fabricate. In general, informal observation of the teams showed that simpler devices generally did better than others in both the contest and in grading.

Not surprisingly, one of the key guidelines in Design for Assembly (DFA) methodology (Boothroyd and Dewhurst, 1989; Ullman, 2003) is the minimization of part count. In DFA, it is often the case that part count is reduced by attributing additional functionality to existing parts. In this study, the complexity of parts themselves was not assessed, so it is not known whether a part was intended to serve multiple functions, or only one.

This study also shows a positive association between designs that limit the number of parts added over time and design outcome. The steady increase in parts over milestones suggests that part fabrication was likely for new components. However, this was likely a substantial amount of *refining, testing, and replacement* of existing parts in addition to the creation of new components, although just how much of this activity occurred was not tracked.

4.2 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. Intuitively, it would make sense that spending more time on a project would lead to a better design result. This belief was by 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.

In Class 2, it was found that spending *less* time on fabricating a prototype was correlated with better contest results as discussed above. This is notable because the percentage of time spent by the teams on fabrication was greater than the other three activities combined. The *less* time spent in building a design, the *better* the ranking in the final design contest. While this may be counterintuitive, it could be seen as 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, including fabrication.

There was, however a very different correlation for total fabrication time in Class 1. In Class 1, there is a positive correlation early on with design outcome, while around the same time period, the correlation is negative in Class 2. Class 2 spent more time total, and slightly more time as a percentage, on fabrication than Class 1 did. This additional time on fabrication in Class 2 could imply a number of things: that Class 2's projects were more ambitious than Class 1's, that Class 2's students were less skilled at fabrication and required more time to complete their projects, or that Class 2's students simply chose to spend more time in the machine shop. We also know that Class 2's overall grade was slightly lower than Class 1's.

In this study, the overall quantity of time spent on all activities in the project correlated in a statistically significant, negative way with contest performance in Class 2. Again, this is somewhat unexpected, 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 debug. 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. Time is not a proxy for quality. One can spend endless hours in the machine shop and still not produce a good design.

For Class 1, the correlation for overall time was also negative, but not in a statistically significant way. This discrepancy may be partially explained by the fact that Class 1 spent less time overall than Class 2, which could be interpreted to mean that they 'worked smarter'.

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. This is consistent with the description of a design activity known as 'patching' (Ullman, 2003) during which a design is altered without affecting its level of detail. This is different than 'refining', in which more detail is added to a design. In general, the goal of patching is to make an existing design 'work' by rearranging existing parts or otherwise modifying them. In a situation where time is of the essence, such as occurs late in the design cycle, patching may be the only way to make a design functional, rather than designing and fabricating new parts.

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.

4.3 Is the timing of activities in the design cycle associated with certain design outcomes?

Finally, in terms of timing, Tables 8 and 9 suggest two trends that, taken together, may point to the same conclusion. Table 8 implies that work performed earlier on (by Week 4) tended to have positive, statistically significant correlations with certain design outcomes. Table 9 shows a similar result for design time for Class 2. In addition, it shows statistically significant, negative correlations with outcome in the later stages of design (Week 3 for fabrication time, and Week 6 for debugging and total time), suggesting that time spent later on is not associated with success.

It is interesting to note that in the early weeks of fabrication, Class 1 exhibits a positive correlation, while Class 2 exhibits a negative correlation. These findings are at odds, but may be explained in part by the way each class apportioned its' fabrication time. Class 1 spent more time proportionally up front than Class 2, suggesting that students in Class 2 may have spent the latter part of the term playing 'catch up'.

This work has implications for the development of software tools to support prototyping. First, the results from this study further validate the notion that simpler devices are associated with better design outcome. It also shows that spending proportionately more time in the early stages of design on prototyping correlates with better design. Taken together, these results imply that early stage prototypes are an important area to focus on. Such prototypes are likely throwaway

prototypes intended to facilitate thinking about a design. Current solid modeling and CAD tools are highly sophisticated, and are excellent for representing designs at their later stages, but they require a level of effort, certainty and refinement in a design that can make them a poor choice for an early stage prototype. This study points to a need for research in and development of software tools to better support early stage concept generation and prototyping.

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