A Statistical Analysis of Student Design Projects:

Helping Good Design Processes Become Better

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October 13, 2005

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Abstract

This paper reports on an analysis of the relationship between key engineering design process characteristics and measures of client satisfaction and design quality. Journal data from 18 senior capstone design projects were codified according to design abstraction and design activity. A regression analysis indicates that approximately 60% of the variance in design outcome can be explained by a subset of the process variables. We find problem definition and idea generation at the conceptual level combined with detail level engineering analysis associate with higher levels of customer satisfaction, while refinement of conceptual ideas, and engineering analysis at the system level associate most positively with design quality. The data codification and analysis procedures are presented, and the implications of the findings discussed.

Introduction

Numerous authors propose models for "good" design process. While there appears to be a fair bit of agreement as to what activities design engineers engage in to provide engineering solutions to open-ended problems, the details of task division, allocation, and sequence remain various. We believe that this ambiguity reflects not a number of incorrect models, but rather differing emphases, audiences, and purposes. To illustrate this proposition, we created two statistical models using different measures of design "goodness"—client satisfaction, and design quality as evaluated by practicing professional engineers. Nearly 60% of the variance in the quality measures can be explained by process measures alone; interestingly, the significant predictor variables in the two models do not overlap. This suggests that designers may be able to tailor their processes to prioritize different design objectives, and that the definition of a "good" design process is situationally dependent.

This paper develops out of a multi-year study conducted at Montana State University (MSU) to examine the processes used by senior mechanical engineering students during their capstone course. Our data set consists of design journal data from 18 student projects, each spanning fifteen weeks. Within the sample, all teams were advised to follow what might generally be called 'good' design practices. However, teams' processes varied significantly, and as did their final outcomes.

We have codified the journal data according to design abstraction level and basic activity type. We then examined the relationship of aggregated process characteristics and the two response variables using a stepwise linear regression technique, making a local estimate of the importance of more effort in certain activity/abstraction combinations on the two responses independently. The analysis suggests that the interaction between task type and level of abstraction significantly impacts the results of design team efforts.

The following section highlights the work of several prominent authors on design theory and process. We then describe the data collection methods used for this study, followed by a presentation of the results from a multivariate linear regression analysis. We conclude with a discussion of the implications of these results and possible directions for future work.

Background

While not entirely comprehensive, the body of design methodology literature might be broken into two camps: those prescriptively defining the design process, and others engaged in empirical research on design process. Both between and within these categories, certain ambiguities regarding the proper approach to design are evident.

In the former case, Otto & Wood [19], Pahl & Beitz [21], Pugh [22], Samuel & Weir [24], and Ullman [29] below, to name only a few, have all presented texts on how to approach an engineering design problem. Even within this limited set, we see notable contrasts. Pahl & Beitz, for example, describe design as consisting of the primary phases illustrated in Figure 1. By comparison, Ullman appears to emphasize more the production involved in practical design, heading his presentation of the generic mechanical design process with the phase titles in Figure 2.

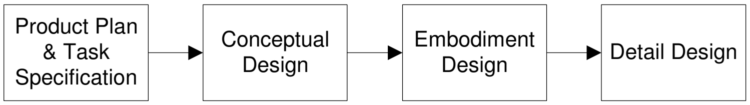

Figure 1. Main Stages of the Design Process, Pahl & Beitz [21]

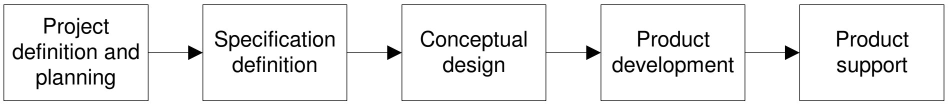

Figure 2. The Mechanical Design Process, Ullman [29]

At this high level, both authors agree on the need for early problem definition and conceptual design, but differ on the phases included beyond that. Pahl & Beitz include an entire phase devoted to embodiment design, intermediary to conceptual and detailed design, while Ullman's outline does not. On the other hand, Ullman allocates a segment of the design process to product support and eventual retirement. To the best of our knowledge, neither model is inherently superior, but instead, each reflects differing emphases and priorities.

Otto and Wood [19] seem to support this thought, as their text argues that the sequence and content of engineering design processes varies with the circumstances. While the authors outline a high-level sequence (see Figure 3), they state that any more detail will lead to a representation that is only situationally appropriate.

Figure 3. Phases in a Product Development Process, Otto and Wood [19]

This general outline of the design process reiterates the need for early problem definition, but the subsequent development and implementation leaves what may be the majority of design activity unspecified.

To be fair, the activities described within the steps/phases of the different models do bear some resemblance. And even though many of the models are presented as sequential flows, authors generally agree that actual design processes never adhere rigidly to the model as presented. The model is more of a general guide than a detailed roadmap. But, while substantial agreement may exist between authors, that concurrence is far from complete.

Some contrasts might be explained by historical development of design theory, as with the comparison of American and European design theory that Birmingham, et al [5] make. Alternatively, specific models may be appropriate to limited domains/situations, as suggested by Whybrew et al. [30]. However, as several authors have pointed out [3], [10], [11], [25], creating a consistent set of rules for design, described in a common language would seem desirable. The contributions of these many authors, while each valuable in their own right, seem to still lack congruence and suggest there is still much we do not understand about engineering design.

The growth in empirical design research over the last decade has uncovered a number of insights, but has done little to resolve the apparent discrepancies and ambiguities in the prescriptive literature. Adams, et al [1], for example, investigated differences in the design behavior of freshman versus senior engineering students, finding, among other things, that better quality designs result from processes that transition more frequently between tasks. Their data show, for example, that student designers who produced higher quality designs tended to spread problem definition activities out over the length of the design exercise; whereas students producing lower quality designs tended to conduct nearly all of their problem definition activity all at once, early in the problem-solving exercise. This would appear to contrast significantly with sequential flow models of design that suggest to first define the problem, then generate ideas and so forth.

Where some authors have found that distributed activities seem to improve design results, other results might support more segregated models. Restricting themselves primarily to early or conceptual design, Nagai and Naguchi [20] and Liu and Bligh [18] have argued that ideas should be generated iteratively, through a repeated cycle of tasks. Nagai and Naguchi emphasize the gradual refinement of the design description, while Liu and Bligh highlight the interchange of divergent and convergent activities. The argument that fixed blocks of tasks enhance the quality of results seems to support the sequential flow model of design.

These differing approaches might reflect the techniques that designers chose to cope with what Dorst [9] calls the underdetermined nature of design problems, where the very flexibility of the design problem makes it more difficult to solve. In this view, different patterns of activity might be illustrating alternative search paths through the design or problem spaces for enough information to define a solution. Gero and Kannengiesser [12] provide a more elaborate example of this concept, re-casting the problem-solution dichotomy as a division between external, expected, and interpreted worlds with tasks bridging the gaps between.

While the immediately preceding discussion represents a group of researchers with a design activity focus, another group of researchers seem to emphasize problem scope. Many designers chose to decompose problems to more tractable levels, and authors like Chen et al. [7] and Sosa, et al. [28] have investigated this tendency to modularity in product design, proposing tools to break design problems and solutions unto sub-problems and sub-solutions with clear, simple interfaces as a way to improve design performance. Gershenson et al. [13] and Kusiak [17] reinforce the importance of these techniques, suggesting that modular design enhances product variety and perhaps success in general. This view does not seem represented in the prescriptive literature. The proposed models seem to have just one overall problem in mind. It is also not clear how the modular strategy interacts with the actual activities of designers—what kinds of problem definition or idea generation activity should precede or follow the chunking of the problem into pieces, and are they different, as one example.

Taken in comparison to other arguments for the importance of iterative or exploratory design ([8], [9]), we might ask how to reconcile the differing emphases on an exploratory design process where sub-systems interact and evolve together with a method of isolating subproblems to minimize their interactions. This contrast might be explained by either historical or ideological differences, as Bucciarelli [6], Rohatynski [23], or others [5], [9] outline, but in search of a consensus on ‘good’ design process, we might hope to find a consensus model, rather than several candidates.

Further complicating the landscape of design literature is a set of researchers focused on personal characteristics of designers. Quite a bit of work has investigated the role of design experience or expertise. Ahmed & Wallace [2], for example, investigated the knowledge needs of novice designers in the aerospace industry, showing that less-experienced designers often fail to understand their own knowledge needs. Smith and Duffy [26] make a case for the utility of re-using knowledge of previous efforts in similar problems later encountered by designers. Cross [8], in his summary of research on design expertise, describes what appear to be the characteristics of expert designers. One of these characteristics, as an example, is that expert designers tend to fixate fairly early on a design concept, and are fairly reluctant to let go.

What’s less clear is the utility of this information to help designers improve performance. How applicable are so-called “expert” processes for novice designers? Kurfman et al [16] demonstrated that use of certain tools can enhance the repeatability of design results and their communication to others. Bender et al. [4] similarly found that students educated in design methods did seem to generate better embodiment designs, but conversely, seemed to do less well at concept generation. This suggests that teaching novice designers expert techniques has an ambiguous effect on design quality. Further, we have little information on the interaction between expertise and “expert” techniques, although the investigation by Bender, et al. suggests a generally positive effect from expertise independent of design method education.

One approach to resolving the contrasts between full-process models, and a framework in which to understand the varied outcomes of focused empirical studies, is to experimentally determine the importance of certain features of the design process. We theorize that an examination of the design process and its outcome can illustrate a) how important design process is to outcome, and b) which elements of the design process most impact design results. In so doing, the results may provide recommendations for which design procedures to adhere to in pursuit of quality designs.

Data Collection

In order to extend our investigation, we collected data on the design processes followed by senior mechanical engineering students at Montana State University over the course of capstone design projects from 1999 to 2003. Students maintained design journals as part of their coursework, and these journals served as a record of the design process each team of two to four followed over the semester. After the collection of these journals for final review, the information they contained was encoded and aggregated to the team level for analysis. We then collected measures of client satisfaction and design quality on the teams' final products. This section presents the design process data collection methods, summary statistics, and outcomes measurement methods.

Design Process Data

In order to capture the process that the student designers followed, we chose to utilize design journals for several reasons. First, design projects extend across a fifteen week semester, with student efforts occurring at any moment of the day (or night); over such an extended time period, it was deemed impractical to directly observe the designers' activities. Student journals allow us to gather data, in real time, on multiple projects over an extended period. Second, the presence of an observer can influence the procedure designers follow. By asking students to record their own activities, we can capture multiple corroborating accounts from the designers' viewpoint, hopefully providing an accurate view of the true design process followed.

After an initial in-class discussion of the journals and journaling standards, students were asked to maintain their records of the design process, receiving feedback through periodic evaluations of their journal's quality. Coaching prioritized thoroughness, insight, and proper form (dates/times/other labels). Over the course of each semester, researchers observed team meetings for a subset of the current projects, providing another check on journal accuracy, in combination with periodic evaluations, and later comparison between journals.

Following their project's completion, students submitted their journals for a final review, after which the data was reviewed and coded, entry by entry, according to a three by four matrix of level of abstraction versus activity type as shown in Table 1. A complete discussion of the development behind this schema can be found in [27].

Table 1: Coding Matrix

Design Activities	*Levels of Abstraction* **Concept (C)**	 **System (S)**	 **Detail (D)**
Problem Definition (PD)	C/PD	S/PD	D/PD
Idea Generation (IG)	C/IG	S/IG	D/IG
Engineering Analysis (EA)	C/EA	S/EA	D/EA
Design Refinement (DR)	C/DR	S/DR	D/DR
Non-Design Activities			
Project Management	PM		
Report Writing	RW		
Presentation Preparation	PP		

As illustrated here, we identify three levels of abstraction. Concept-level design addresses a problem or sub-problem with preliminary ideas, strategies, and/or approaches. Common examples include identifying customer needs, establishing the design specifications, and generating and selecting concepts. System-level design defines the needed subsystems, their configuration and their interfaces. Detail design activities focus on quantifying specific features required to realize a particular concept, for example defining part geometry, choosing materials, or assigning tolerances. This three-level classification of the design process closely resembles the division Pahl and Beitz make between conceptual, embodiment, and detail design [21], although our emphasis on level of abstraction is intended to allow for any category of activity to occur at any point in a design project's timeline, despite their strong association with similarly named project phases. Similarly, Cross' representation of the design process (cited in [5])identifies a continuum between overall and sub-problems.

We also delineate four categories of design activity. Problem definition (PD) implies gathering and synthesizing information to better understand a problem or design idea through activities such as: defining customer requirements, identifying deliverables, and researching existing technologies. Activities in idea generation (IG) are those in which teams explore qualitatively different approaches to recognized problems, as with brainstorming activities and catalog searches. Engineering analysis (EA) involves formal and informal evaluation of existing design/idea(s), e.g., mathematical modeling and decision matrices. Finally, design refinement (DR) activities include modifying or adding detail to existing designs or ideas, examples being deciding parameter values and creating engineering drawings using computer-aided design (CAD) software. These four activities can be used to reflect divergence/convergence in the problem space or solution space. PD requires the definition of an acceptable search range in the problem space (divergent), while EA reduces that space based upon the current fit with the solution (convergent). Similarly, IG expands the solution space under review, and DR narrows it down again.

Finally, the coding scheme designates symbols for non-design activities associated with project management and project delivery so that every entry could be assigned a code. Project management (PM) covers project planning and progress evaluation, including: scheduling, class meetings to discuss logistics and deadlines, and reporting project status. The delivery category is for activities associated with interim and final report writing (RW) and final presentation preparation (PP). A preliminary analysis attempting to relate these and other non-design measures to process outcome found no significant relation between these non-design variables and the product quality, leading us to discard them from further analyses.

Each project, and the multiple accounts documenting it from the different students involved, was examined by a primary coder whose work was periodically assessed by a chief reviewer as a consistency check between projects. Any questions regarding the appropriateness of a coded entry were debated to agreement between the primary coder and the chief reviewer. As an additional method of ensuring journal quality and consistency, reviewers cross-checked journals against one another for omissions or disagreements on time and activity. Conflicting records were resolved where a weight of evidence supported one account, or averaged where no case dominated.

For each distinct activity-abstraction code in a given entry, an estimated duration was recorded as well, based on the start and end times that students listed, and subdividing multi-code entries by the page area representing each code.

Following this complete coding, data for each project was recorded in a spreadsheet documenting the day-by-day work of the design team, with entries separately listed to show the date of activity, its assigned code, and the time associated with that effort. Finally, an aggregate grid, indicating the total time observed in the project for each combination of activity and abstraction, was generated by summing the raw hours recorded.

Summary Statistics

After removing one project as an outlier due to an unusual process and exceptionally low quality scores, the resulting data set describes 18 design projects encoded through the twelve design activity variables summarized in Table 1. Table 2 presents the means and standard deviations of the process variables, along with their intercorrelations. The data are aggregated to the project level (meaning, for example, that the average team spent 38.16 person-hours on concept-level problem definition activities over the length of the project). The sample represents over five thousand person-hours of design-related activity by the individuals involved. Project length averaged 310.61 person-hours of design activity, with a maximum of 743.29 hours and a minimum of 172.37 hours.

Overall effort is dominated by D/DR, D/EA, C/PD, and D/PD, suggesting a strong tendency for students to emphasize detailed work, perhaps following early PD. System-level activities constitute a minority of student effort, and are highly variable, as illustrated by the standard deviations relative to the means of those variables.

The means presented in Table 2 suggest that concept-level design efforts are generally dominated by problem definition and idea generation, while detailed efforts primarily appear as engineering analysis and design refinement. From this, we observe that students seem more prone to divergent, possibly exploratory, activities at higher levels of abstraction, and similarly tend to pursue convergent activities in their detailed design efforts. Examining the pair wise relationships between process variables, we see multiple strongly positive correlations, and few strongly negative relations. The correlation between given task types seems to change with abstraction levels, one example being how C/PD correlates strongly to C/EA, while S/PD correlates weakly with S/EA.

Table 2: Process Variable Correlations and Parameters

	C/PD	C/IG	C/EA	C/DR	S/PD	S/IG	S/EA	S/DR	D/PD	D/IG	D/EA	D/DR
C/PD												
C/IG	0.33											
C/EA	0.74	0.02										
C/DR	0.32	0.61	0.25									
S/PD	0.40	0.43	0.18	0.49								
S/IG	0.60	0.12	0.52	0.17	0.36							
S/EA	0.15	0.34	0.25	0.08	-0.04	0.20						
S/DR	0.07	0.51	-0.25	0.51	0.80	0.17	-0.11					
D/PD	-0.09	0.55	-0.02	0.16	0.01	-0.22	0.20	0.11				
D/IG	-0.08	0.31	-0.04	0.30	-0.04	0.14	0.24	0.14	0.45			
D/EA	-0.11	-0.04	0.10	0.10	-0.31	-0.28	0.45	-0.37	0.01	0.14		
D/DR	-0.01	0.40	0.01	0.48	-0.13	0.06	0.67	0.03	0.13	0.58	0.50	
Mean (hrs)	39.59	14.15	8.44	3.34	5.77	7.14	2.73	7.78	27.23	10.83	76.69	130.96
Std. Dev.	19.41	8.86	9.81	5.25	10.35	4.79	3.18	9.17	19.01	9.43	49.58	100.91

Project Outcomes Data

The results of each project were evaluated using two measures: a client satisfaction score and a design quality score (for a complete discussion of the development of these tools, see [15]). Client satisfaction scores were generated from a questionnaire using a five-point Likert scale to evaluate issues in six areas, with responses recorded by a researcher speaking to the design project sponsor by telephone. Specific feedback documented the client's impressions regarding project quality, cost, complexity, and deliverables, as well as overall impressions and team/client involvement. We used Cronbach's alpha as a measure of internal consistency, and reduced the data set to the two most reliable measures. Final client satisfaction scores derive from summing these two composite measures, one for overall satisfaction (α=0.70, 6 questions) and another for the customer's assessment of product quality (α=0.78, 2 questions). For this sample set, we observed CSQ scores between 6.13 and 10.00, with a mean of 8.42.

To assess design quality, we contracted four professional engineers to independently evaluate the students' final reports using a design quality rubric (DQR). Each project received at least two assessments, with the final score being the average of all evaluations. The DQR contained five metrics each on a seven-point scale. DQR measures represent the views of professional engineers regarding the degree to which each design team met the objectives of project requirements, feasibility of the proposed solution, creativity, simplicity, and their overall impressions. Projects in the data set earned DQR scores between 3.20 and 6.00, with an average of 4.70.

Analysis & Results

We modeled the data with a multivariate regression technique, using the 12 process variables listed in Table 2 as the independent variables, and the client satisfaction and design quality scores as response variables. We used a reverse-elimination procedure to incrementally remove variables from the models until the p-values associated with all remaining variables fell under our threshold of 0.10. Table 4 summarizes the final models describing client satisfaction and design quality. Five variables failed to show significance in either model and do not appear in the summary table: conceptual engineering analysis (C/EA), system-level problem definition (S/PD), system-level design refinement (S/DR), detailed problem definition (D/PD), and detailed idea generation (D/IG). A review of the residual plots found no significant patterns.

Table 3. Final Regression Models

Independent Variables	Client Satisfaction Model	Design Quality Model
Intercept	6.09**	4.60**
C/PD	0.025*	
C/IG	0.077**	
C/DR		0.086**
S/IG		-0.061**
S/EA		0.091**
D/EA	0.012**	
D/DR	-0.005*	
R^2	0.594	0.579
Standard Error	0.874	0.530
Degrees of Freedom	13	14
n	18	18

* p ≤ .10, ** p ≤ .05

The analysis identifies three variables as positively related to customer satisfaction, those being conceptual problem definition (C/PD), conceptual idea generation (C/IG), and detailed engineering analysis (D/EA). Detailed design refinement seems negatively correlated with customer satisfaction, despite relatively strong positive correlations to C/IG and D/EA (0.40 and 0.48, respectively).

Design quality, as measured by the DQR, associates positively with conceptual design refinement (C/DR) and with system-level engineering analysis (S/EA). By the same token, it correlates negatively with system-level idea generation (S/IG). The process measures explain nearly 58% of the variance in design quality scores.

As a final result, we find no overlap in significant variables between the customer satisfaction and design quality variables. This reinforces earlier findings that suggested these two measures may be fundamentally different [15]. Further, we observe that customers appear to favor design processes involving extensive conceptual development supported by detailed analyses, while technical quality may depend more on early refinement of ideas, and evaluation of systemic issues, rather than just detailed ones.

Discussion

Problem definition and idea generation were the most prevalent activities at the conceptual level of design work, correlating well with our expectations that students would prefer these activities to the more critical and concrete EA or DR. At the system-level, idea generation, design refinement, and problem definition appear predominant, if only relative to the nearly nonexistent engineering analysis occurring at that level of abstraction. Since system-level activity involves the subsystems and/or interfaces present in a design, this slight bias towards more generative activities may indicate that student designers feel more comfortable hypothesizing a system rather than critiquing or evaluating, suggesting a 'guess and check' approach to system-level issues rather than a method of analytical reduction of the problem space. In keeping with an intuitive sense of design strategies, engineering analysis and design refinement occupy most detailed design effort. Overall, these averages appear to verify that student teams tended to follow accepted design strategies emphasizing early problem definition and ideation, with later, iterative refinement being focused in the detailed design.

Taking into account only process variables describing the allocation of team efforts to various combinations of activity type and abstraction level, our models explain approximately 60% of the variance in each of the two quality responses. Preliminary analyses examining the importance of non-design variables like team size, hours spent on report writing, or gender balance found no significant relationship between these elements and end project quality. While we might like to see a more powerful model in place, we feel that explanatory power covering the majority of the variation with this limited set of variables highlights the importance of process, and specifically its cognitive and procedural features, on design outcomes.

Within our models, the relative magnitudes of the regression coefficients suggest that high to middle abstraction activities impact both customer satisfaction and design quality more dramatically on a per-hour basis than those at the detailed level. This reinforces again the importance of early design work establishing the concept and architecture, and may suggest that design process models incorporating an intermediate design phase may more closely prioritize valuable efforts, as with Pahl & Beitz [21], or Dym [10].

Intuitively, better designers should behave in a more ‘expert’ fashion. Our results indicate that among novice designers, superior customer satisfaction indices are associated with problem definition and idea generation at the conceptual level, critical analyses at the detailed level, and reduced refinement at low levels of abstraction. Higher design quality scores correlate with increased conceptual design refinement and system-level engineering analysis, and with reduced ideation at the system level.

According to Cross [8], expert designers typically act in a more exploratory fashion, which is certainly in keeping with our findings as long as that investigation is restricted to higher abstractions. This restriction is reinforced by the relatively strong negative impact of system-level idea generation on design quality, and may suggest that systematic issues should be evaluated as refinements on existing concepts, rather than generated spontaneously. Adams, et al. [1] suggest that frequent transitions between activities are important, and our analysis does not dispute this, although it does indicate that most of the tasks design teams can pursue are either insignificant or harmful to product quality/customer satisfaction. Their argument that reflective behavior is important to design success suggests that our model of design process might be enhanced by some measure of reflective capacity, which at this point is beyond our analysis.

Our model relating design process to customer satisfaction suggests that customers value extensive efforts to accurately capture their high-level requirements, many distinct alternatives to answer their needs, and a strong analytical case supporting the design team’s recommendations. Tellingly, we observe that problem definition and idea generation at lower levels of abstraction seem insignificant, reinforcing the somewhat intuitive expectation that customers may not care about the details of the implementation except insofar as they have apparently been thoroughly investigated.

In evaluation of process’ impact on design quality, the emphasis on conceptual design refinement suggests that final design quality improves as designers explore variations on primary concepts. Design teams may benefit from reviewing highly abstract alternatives even before they investigate them at more detailed levels. The positive association between design quality and S/EA, however, argues that design quality may be better served by analyses that expose interface issues of a design than conceptual or detailed evaluations. We take this to mean that highly abstract representations of the design object may be sufficient for useful investigation of the system-level issues within that design.

The negative association between D/DR and CSQ score might be explained by our observation that design teams often attempt to counter problems discovered late in the design process with detailed revision of the design. Rather than being a causal variable with regard to customer satisfaction as a first impression might suggest, it is possible that the increased levels of D/DR associated with low CSQ scores are reflective of problematic early design. The relatively strong correlations between C/IG, C/DR, S/EA, and D/IG with D/DR might also lead us to conclude that D/DR is a necessary, if unproductive activity following extensive exploration of the problem space, which we find to be beneficial to designers.

The negative impact of S/IG in the DQR model may be local phenomena of our sample set, as intuitively, we might expect systematic alternatives to lead to better overall results. With the current information available, it is difficult to conclusively explain this point, but one possible rationale might be the relative unfamiliarity of students with the solution spaces they explore. It is possible that expert designers might see far better results in this activity/abstraction combination if domain experience significantly impacts the productivity associated with certain tasks, as implied by Ahmed and Wallace's results [2].

As mentioned previously, we find no overlap in significant predictor variables between our models of CSQ and DQR. This result is slightly counter-intuitive, as we might expect similar activities to enhance both customer satisfaction (if only indirectly), and design quality. Some of this divergence might be attributed to the lack of correlation between CSQ and DQR (ρ = 0.41), but that desynchronization is suggestive, rather than conclusive. Further insight might be gained from an inspection of the correlations between these predictor variables, illustrated in Table 4.

Table 4. Predictor Variable Correlations

			Design Quality		
	Variable	sign	C/DR +	S/IG -	S/EA +
Customer Satisfaction	C/PD	+	0.32	*0.60*	0.15
	C/IG	+	0.61	*0.12*	0.34
	D/EA	+	0.10	-0.28	0.45
	D/DR	-	*0.48*	0.06	*0.67*

As summarized here, activities enhancing one quality measure do not always positively correlate with similarly supporting variables for the other quality response. Specifically, we observe that C/DR associates positively with design quality and with increased D/DR, the latter being associated with reduced customer satisfaction. This relationship might be described as a competitive contrast or tradeoff between the two quality objectives. Italicized values in Table 4 indicate the presence of these tradeoffs, and show that of the twelve interrelationships present, one-third appear competitive in some degree between CSQ and DQR. The conflicting nature of these design variables' impacts may serve to explain some of the difference both in process models and in the outcomes they predict.

Our discarded data point describes a substantial departure from the procedures and outcomes described above. The team spent below-average time on problem definition and idea generation activities at higher levels of abstraction, with above average efforts in engineering analysis and design refinement at those same levels. At the detailed level, the designers reversed this policy, with above average effort devoted to problem definition and idea generation, but less effort in analysis and refinement. Following this strategy, they achieved CSQ and DQR scores of 5.38 and 1.80, respectively; significantly below the average scores of 8.33 and 4.62.

While limited by the sample size available, these results seem strongly suggestive of a general refinement on the popular design process model, supporting both customer satisfaction and design quality. Applying the results of both our regression for CSQ and that for DQR, we find a unified set of recommendations for design teams. Early problem definition and idea generation are undoubtedly important, but our investigation suggests that those activities should be limited, in some part, to conceptual efforts, particularly avoiding excessive ideation at the system level. Similarly, our evidence argues that more critical, analytical activities should be restricted to reviews of the design at the system and detailed levels of abstraction. This may reflect an inability by designers to extract useful information from conceptual representations, or may simply illustrate that these activities are inherently suited to representations expressing systematic relations or detailed quantities.

That being said, the analysis takes into account primarily linear relationships within the scope of the data set. Our results are at this point generalize only to senior mechanical engineering students at MSU-Bozeman, and assume that we are modeling a fairly localized region of the complex space that is design. While our results show that some combinations of activity and abstraction correlate with improved quality indices, we have yet to evaluate the tradeoffs present between these variables and the constraints of precedence or sequence that are likely to impact a truly complete model of design process. Further work is necessary to quantify how the linear estimates obtained through our regression are constrained by minimal/maximal allowable efforts at any given cell in our summary matrix.

Specific elements in our results remain counter-intuitive and unexplained. While we can hypothesize the rationale behind these findings, we lack as yet strong evidence in support of these theories. Some of the ambiguity in our results might be clarified by analyses taking into account the expertise or domain knowledge of designers, the interactions of process variables, or the features of the design problems involved, which we have only partially investigated as yet.

Future work must expand beyond the limitations of this study in order to make our results applicable to engineering design at large. More extensive investigation including other student bodies and/or professional teams, alongside non-linear techniques of analysis, and possibly some non-process variables, are necessary to make this study truly general to the design community.

Conclusions

Our results fall out into several major points. First, we find that we have an example of a team that followed an unusual design process with very limited early conceptual problem definition and ideation, followed later by extensive efforts in these tasks at the detailed level. Their project results yielded very low scores for the CSQ and DQR indices, confirming once again some of the classical advice to designers.

Second, our models that develop for both CSQ and DQR responses show little similarity to each other. The differences in intercept might be expected due to the different scaling the two responses used, but aside from that, we find different combinations of activity and abstraction important to these measures. Within the context of capstone senior design projects, clients seem to value solutions produced through conceptual problem definition and ideation, with supporting engineering analysis. In contrast, reviewing engineers favored projects developed with more conceptual design refinement and system-level engineering analysis. These results emphasize that different processes lead to different types of quality, and an inspection of the relationships between these variables suggests that different processes may even conflict. The proper methods for solving a given design problem may depend heavily on the intended audience for the result, in defiance of the statement that there is unqualified ‘good’ design process.

In practice, this emphasizes the importance of clearly identifying the end customer of a product, and their priorities with regard to the design. Early problem definition is identified as important by many authors, and our results both confirm this in the context of customer satisfaction, and reinforce the issue by suggesting that certain processes or quality types may compete with others.

The significance of abstraction as a refinement on activity descriptors argues for its importance in design education as well. Certain activities appear to positively impact design more when conducted at specific levels of abstraction. Particularly with novice or student design teams, the additional descriptive power afforded by levels of abstraction may be helpful in describing important tasks and planning design efforts, and in educating designers as to where their efforts will most advance the design.

In sum, this study confirms the importance of a standard design process emphasizing early conceptual efforts and later detailed refinements. However, within the bounds of a fairly normal process, our findings suggest that better design results can be achieved by focusing design team efforts on specific combinations of activity and abstraction level. We also observe that the significance of tasks to design quality or customer satisfaction is closely related to the abstraction level at which they are performed. Finally, we note that design process itself is central to the effectiveness of design efforts. The overall process characteristics leading to a product seem to have great explanatory power regarding that product’s quality in the eyes of both technical professionals and customers.

References

[1] Adams, R. S., Turns, J., and Atman, C. J., *Educating effective engineering designers: the role of reflective practice*, Design Studies, V24 N3 p275-294.

[2] Ahmed S. and Wallace K.M., *Understanding the knowledge needs of novice designers in the aerospace industry*, Design Studies, V25 N2 p155-173.

[3] Bender, B., *Task design and task analysis for empirical studies into design activity*, Journal of Engineering Design, V14 N4 p 399-408.

[4] Bender, B., Kammerer, U., Pietzcker, F. P., Hacker, W., and Blessing, L. T. M., *“Successful Strategies for Complex Design in Early Phases of the Product*

Development Process – An Empirical Study", 13th International Conference on Engineering Design, Glasgow, UK.

[5] Birmingham, R., Cleland, G., Driver, R., and Maffin, D., 1999, *Understanding Engineering Design: Context, Theory, and Practice*, Prentice Hall Europe, Hertfordshire.

[6] Bucciarelli, L. L., *Designing and learning: a disjunction in contexts*, Design Studies, V24 N3 p 295-311.

[7] Chen, Li, Ding, Zhengdong, Li, Simon., *Extended Hierarchical Cluster Analysis for the Decomposition of Complex Design Problems*, Proceedings of DETC 03.

[8] Cross, N., *Expertise in design: an overview*, Design Studies, V25 N5 p 427-441.

[9] Dorst, K., "*Design, Science, and the Problems of Undetermined Problems*", 13th International Conference on Engineering Design, Glasgow, UK.

[10] Dym, C. L., 1994, *Engineering Design; A Synthesis of Views*, Cambridge University Press, New York.

[11] Friedman, K., *Theory construction in design research: criteria: approaches, and methods*, Design Studies, V24 N6 p 507-522.

[12] Gero J. S. and Kannengiesser, U., *The situated function-behaviour-structure framework*, Design Studies, V25 N4 p 373-391.

[13] Gershenson, J. K., Prasad, G. J. and Zhang, Y., *Product modularity: measures and design methods*, Journal of Engineering Design, V15 N1 p33-51.

[14] Horvath, I., "*A Contemporary Survey of Scientific Research into Engineering Design*", 13th International Conference on Engineering Design, Glasgow, UK.

[15] Jain, V. K., 2003, "*Relating Design Process to Design Outcomes in Engineering Capstone Projects*," M.S. thesis, Montana State University, Bozeman, Montana.

[16] Kurfman, M. A., Stock, M. E., Stone, R. B., Rajan, J. and Wood, K. L., *Experimental Studies Assessing the Repeatability of a Functional Modeling Derivation Method*, Journal of Mechanical Design, V125 p682-693.

[17] Kusiak, A., *Integrated product and process design: a modularity perspective*, Journal of Engineering Design, V13 N3 p 223-231.

[18] Liu, Y. C. and Bligh, T., *Towards an 'ideal' approach for concept generation*, Design Studies, V24 N4 p 341-355.

[19] Otto, K. & Wood, K., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, New Jersey.

[20] Nagai & Naguchi, *An experimental study on the design thinking process started from difficult keywords: modeling the thinking process of creative design*, Journal of Engineering Design, V14 N4 p 429-437.

[21] Pahl, G. and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer, London.

[22] Pugh, S., 1991, *Total Design; Integrated Methods for Successful Product Engineering*, Addison-Wesley Publishers Ltd., Cornwall, Great Britain.

[23] Rohatynski, R., "*Diagnosing the Gap Between Methodology of Engineering Design and Industrial Practice*", 13th International Conference on Engineering Design, Glasgow, UK.

[24] Samuel, A. and Weir, J., 1996, *Introduction to Engineering Design, Modelling, Synthesis, and Problem Solving Strategies*. Butterwoth-Heinemann

[25] Samuel, A., Weir, J. and Lewis, W., "*A Common Language for Engineering Design Practice and Research*", 13th International Conference on Engineering Design, Glasgow, UK.

[26] Smith, J. S. and Duffy, A. H. B., "*Re-Using Knowledge – Why, What, and Where*", 13th International Conference on Engineering Design, Glasgow, UK

[27] Sobek II, D.K., 2002, "*Preliminary Findings from Coding Student Design Journals*," 2002 American Society of Engineering Education conference, Montreal, Canada.

[28] Sosa, M. E., Eppinger, S. D. and Rowles, C. M., *Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions*, Journal of Mechanical Design, V125 p240-252.

[29] Ullman, D.G., 2003, *The Mechanical Design Process*, McGraw-Hill, New York.

[30] Whybrew, K., Shaw, A., Aitchison, D., and Raine, J., "*Use of Design Tools and Methodologies for Rapid Product Development in the New Zealand Manufacturing Industry*", 13th International Conference on Engineering Design, Glasgow, UK.