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**RELATING DESIGN ACTIVITY TO QUALITY OF OUTCOME:
A REGRESSION ANALYSIS OF STUDENT PROJECTS**

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ABSTRACT

This study focuses on better understanding the impact of design process behavior on project outcomes, as demonstrated by mechanical engineering students at Montana State University. Using process data gathered from student design journals, and quantitative measures of project results, we examine the relationship between student designer activities and project outcomes through a multivariate linear regression analysis. Results indicate that significant differences exist between customer satisfaction, and design quality as measured by professional engineers. Further, this study finds that client satisfaction increases with time spent on problem definition activities and decreases with concept-level engineering analysis. In contrast, system-level idea generation and refinement activities are the most strongly positively associated activities for design quality, while design refinement at the concept level is a strong detractor.

INTRODUCTION

Design is recognized as an important part of the engineering profession, and is thus a major topic in research regarding both engineering education and commercial practice. One fundamental objective many researchers in either arena pursue is that of improving the process of design to achieve more effective designs efficiently. Whether this improvement manifests along a dimension of cost, quality, or time, the common goal is to optimize design. Many authors have proposed models for a superior design process, but they are usually based on either very small sample sizes, leading to highly specialized recommendations, or on personal experience, which may lead to general models difficult for inexperienced designers to apply. Further, the assertion some authors make that design can only be learned by practice, while

likely valid, needs expanding upon, particularly in the area of recommendations for how to learn good design techniques.

If designers are to improve their processes, they need not only measures of that process and its outcomes, but also an understanding of the relationship between the two. This study attempts to develop some of that knowledge by looking at three specific questions:

1. What behaviors significantly influence the quality of design process outcomes?
2. Given that different measures of outcome quality exist, do different activities contribute to different quality "types", or is there significant overlap?
3. What are the relative impacts of any significant variables on design outcome quality?

In answering these questions, we hope to develop a model that will help designers prioritize their efforts into specific types of activities in order to achieve specific objectives.

BACKGROUND

In recent decades, researchers have taken a number of paths while attempting to describe the design process [1-5]. In particular, the recognition that design may be described as a sequence of specific tasks or behaviors is central to how we commonly define it. Despite this basic agreement, various models delineate the components of the design process differently, emphasizing certain points over others. These specializations represent tradeoffs between generality and ease of application for models, or similarly between the descriptive and prescriptive usefulness of different models. For researchers of design, this means that selecting an appropriate

representation of the design process is critical both to developing an accurate representation of designer behavior and to translating any analysis of that data into useful results.

The key issue here may be the focus of a given representation for the design method. Drawing upon Birmingham, et al's [1] comparison of design process models, and examples presented by Haik [2], it appears that some models have attempted to represent the entire process with only cognitive activities (behaviors), as illustrated by Darke's cycle of Generator->Conjecture->Analysis or Lawson's alternative Analysis->Synthesis->Evaluation. Similarly, Otto and Wood's redesign methodology [3] uses a series of high-level phases to outline the design process. These maps of creative activity describe basic patterns that designers experience in their work, and tend to be powerful, if abstract, descriptive tools. Unfortunately, such a fundamental approach can be difficult to apply prescriptively, as each phase in these lists encompasses an enormous range of activities.

Other attempts to define the design process have focused heavily on tasks or objectives that designers must complete. These models typically have the advantage of easily mapping onto a project timeline for purposes of planning or tracking, but encounter difficulties in the case of iterative loops or rework within the design process. As maps of the activity sequence in design develop these branches and cycles, they may gain accuracy in representing designer behavior, but then lose capacity to clearly advise designers or their managers.

Perhaps in recognition of the advantages offered by each type of model emphasis, some researchers have attempted to capture both of these dimensions in one model. Hall's early 7x7 matrix represented "fine" and "coarse" structures of the process against each other, corresponding to logical sequence and project phases respectively [1]. Similarly, Ullman [5] presents a flowchart-style breakdown detailing several phases of the design project and specific tasks within each. This use of project phases maps closely to a division of design process by cognitive focus; following the intuitive scheme of top-down design. While facing some of the same difficulties that task or behavior-focused models do, combined maps of the design process offer a special advantage for both descriptive and prescriptive use in their ability to capture the interaction between tasks and project phases or cognitive activity.

In terms of defining "good" design, other issues arise. Most models in literature seem to be the work of expert designers or design educators, based primarily on experience. While exceptions exist [6], few models are empirically validated, and those often rely on either small samples and/or contrived design problems of limited scope. It remains a challenge for researchers to define "good" design and how to measure it, especially against the objective of an analytical model relating the quality of a design process to its measurable characteristics.

DATA COLLECTION

Towards this end, we collected process and outcome data from capstone mechanical engineering design projects completed between Spring 2001 and Fall 2002 semesters at

Montana State University. ME 404, the mechanical engineering capstone design class, is a four credit one-semester course. Students divide into teams of two to four with a faculty member as advisor. The projects are industry sponsored, so each team must interact with their client/sponsor to define their needs, devise a solution to meet those needs, and deliver a product (set of engineering drawings and specifications, written report, oral report, and in many cases a hardware prototype) by semester's end.

Researchers have used a number of techniques to collect data on design processes, including interviews, retrospective and depositional methods, and protocol analysis [7-11]. However, for this study, a novel approach was needed to study design process *in-situ*, spread over 15 week time period (one semester), without a specified location or researcher intervention, while capturing exact details when and as they occur.

Design journals kept by individual students provide an alternative approach to data collection that fit our desire to study actual student processes. This data collection technique overcomes many of the drawbacks of other research methods. Compared to interviews, retrospective, and depositional methods, the data is collected in real-time, but unlike observational approaches, this approach does not require specially trained professionals. Like protocol analysis, the data can be readily quantified using a suitable coding scheme, but it requires little researcher intervention during data collection and therefore is a potentially more accurate representation of the actual design process. It is also more feasible to collect a relatively large sample size compared to videotaping or other approaches because the quantity of data captured, while still large, is more manageable.

As with any data collection method, disadvantages to the technique exist. Particularly, journals may be susceptible to "backfilling", the tendency for students to records events, not as they occur, but in retrospect. Backfilling can lead to journals that omit key details; as designers highlight details they view as important to the final results, but often skip over mistakes made and lessons learned along the way. This practice can be discouraged through training and feedback during the design process, but ultimately depends on the designer's commitment to keeping a good journal. Similarly, journals may simply offer an incomplete record of the design process. Where designers either keep imperfect records or are unaware of important information, the journals may fail to capture critical details regarding the development of the design project. Again, training and feedback can help designers overcome at least the former issue, but journal quality ultimately depends upon the designer's effort. Fortunately, multiple accounts from different members of the design team can serve to cover holes in individual records and to corroborate details of the record.

Process Variables

Students were asked to keep individual design journals (notebooks) to document their work over the semester as a part of this project [12]. Journals were periodically evaluated using a rubric to help encourage good record keeping, and students were given specific feedback on the expectations and quality of

their journals. The journals constituted 15 % of the final course grade. At project completion, journals were collected and coded according to the scheme in Table 1, with times assigned according to the start / end times recorded.

Table 1: Coding Matrix

<i>Design Activities</i>			
	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
<i>Non-Design Activities</i>			
Project Management	PM		
Report Writing	RW		
Presentation Preparation	PP		

Each design related activity received two codes. The first is level of abstraction where we identify three levels. Concept design addresses a problem or sub-problem with preliminary ideas, strategies, and/or approaches. Common concept design activities are 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.

The coding scheme also delineates 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. 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.

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).

The process of journal coding proceeded in two stages. First, research assistants familiarized themselves with the projects by reading the final written reports, then coded the data

and captured times by walking through team members' journals in parallel, reviewing all the members' entries for a given day before moving to the next day. Simple rules were devised for allocating time, and resolving discrepancies among the different journal accounts. The principal investigator then reviewed the coding as a crosscheck on accuracy and consistency. The disagreements were solved through discussion and the process continued until mutual agreement was reached. The time data on the various process variables was then aggregated for the project by combining individual journal data. (See [13] for more details on journal coding.)

The current sample includes 14 design projects, documented in 50 design journals. Collectively, the some 5,000 pages of journal entries record over 9,000 person-hours of student work.

Outcomes Data

It seems fair to define a "good" design process as one that leads to a good outcome. Thus, to determine the quality of a design process we need a way to measure the value of the end product. For this study we developed two outcomes measures, client satisfaction and the quality of the final designed product. Consequently, two separate instruments, the Client Satisfaction Questionnaire (CSQ) and the Design Quality Rubric (DQR), were developed, validated and deployed for measuring the client satisfaction and the design quality index quantitatively [6].

The CSQ was developed based partly on brainstorming and partly on previously developed surveys [14-16]. The final version had 20 questions divided across six metrics. The survey was validated prior to implementation using content and face validation techniques. Analytical hierarchy process [17] was used to determine weights for the metrics and the questions in each metric. The respondents received a copy of the survey by fax, then a research assistant walked them through the questions by telephone and filled in the responses by hand.

Once responses were obtained from the project sponsors, the survey data was analyzed for statistical reliability using Cronbach's alpha coefficient [18]. The test illustrated that only two of the six metrics (quality and overall satisfaction) displayed adequate internal consistency and inter-metric consistency. As a result, the satisfaction index was obtained by summing the weighted averages of the two metrics. The final satisfaction scores were on a scale of 1-10 with 10 being the highest. Table 2 displays the actual measures used in the client satisfaction score.

Table 2: Client Satisfaction Metrics

Metric	Measures	Cronbach's α
Quality	The percentage of the design objectives the client thought the team achieved	0.78
	The closeness of the final outcome to client's initial expectations.	
Overall	Design's feasibility in its application and fabrication	0.70
	Client's opinion on implementing the design	
	Client's opinion on students' knowledge of math, science and engineering in developing solutions	
	Overall satisfaction with the design outcome	

Since clients do not always have the background to objectively assess the engineering validity of design recommendations, and since "satisfaction" is relative to initial expectations, we also obtained a third party assessment of design quality on each project. A design quality rubric (DQR) was developed to address this issue with an objective to quantify the final "quality" of the designed projects.

To develop this rubric, we obtained evaluation schemes from mechanical engineering capstone course instructors at 30 top ranking schools, and from several design contests including the Formula SAE (2002), ASAE Design Competition (2002), ASME Student Design Competition (2002), and the MHEFI Material Handling Design Contest (2002). We extracted 23 metrics that were common across the evaluation schemes collected. These 23 metrics were aggregated into six measures: requirements, feasibility, creativity, simplicity, aesthetics and professionalism. Since aesthetics is not a requirement in many of our projects and professionalism deals with things like report quality that do not necessarily directly reflect the engineering validity of the students' work, we further reduced the above to five measures. We replaced aesthetics and professionalism with an "overall impression" question to capture the reviewer's overall assessment, including professionalism and aesthetics as appropriate for each project. The metrics and their definitions are presented in Table 3. A seven-point scale was used for each question/metric with three anchors provided (1: Poor, 4: Acceptable, 7: Outstanding). A brief rationale was requested from each evaluator on each response for the purpose of inter-reviewer comparisons to evaluate consistency among the evaluators.

Table 3: Design Quality Metrics

	Metric	Definition	
Basic	Requirements	The design meets the technical criteria and the customer requirements	
	Feasibility	The design is feasible in its application and fabrication / assembly	
Advanced	Creativity	The design incorporates original and novel ideas, non-intuitive approaches or innovative solutions	
	Simplicity	The design is simple, avoiding any unnecessary sophistication and complexity, and hence is:	
		Practical	Usable
		Reliable	Ergonomic
	Serviceable	Safe	
	Overall	Overall impression of the design solution	

Four engineering professionals were hired to evaluate the design projects from the final reports submitted at the completion of each project. Three of the evaluators were licensed professional engineers, each with over 10 years of experience in design and manufacturing. The fourth had 5 years of experience and was not professionally licensed at the time. These evaluators were asked to evaluate the project outcomes as if they were evaluating actual industry designs while taking into consideration the project duration and budget constraints. Specific instructions were provided to assess the design projects on their outcomes, not on the process. Each evaluator was assigned a number of reports in such a way that each report was evaluated twice to provide redundancy in the measurement. All four evaluators looked at two reports in order to determine inter-evaluator consistency. The quality index for each project was calculated by averaging the scores of the individual metrics, then averaging across evaluators, making the final quality score for each project on a scale of 1-7.

The CSQ and DQR measures demonstrate a weak correlation (0.52) implying they measure different things and could not be combined. Therefore, to study the design processes, two models were constructed with satisfaction and quality as their respective responses. A complete description of the techniques used to code the responses, missing values analysis, descriptive question analysis, and other issues on these instruments can be obtained from Sobek and Jain [19].

ANALYSIS & RESULTS

While the complexity of design suggests that an analytical description relating design process to results might be nonlinear, two possibilities encouraged a linear analysis of the data sample. First, if suitable, a linear model can be easier to interpret and apply. Secondly, the limited ranges and clustering seen in some variables suggested that a linear model

might be able to accurately describe the fairly localized region that our data covers.

A multiple linear regression analysis was performed on the sample of 14 coded projects. First, we ran a model with only the “non-design” variables (project management, report writing, and presentation preparation) as the independent variables. None showed a statistically significant relationship with either client satisfaction or design quality. These variables were eliminated from further consideration.

Two additional models were then developed with customer satisfaction and design quality respectively as the response variables, and the twelve design process variables as the independent variables (i.e., the 3 x 4 matrix in the top half of Table 1). Each independent variable represents the number of person hours spent by a project team on each activity at a given design level. We used a step-wise reverse elimination procedure [20] to develop the final models, starting with the full slate of predictor variables and eliminating one variable at a time until all remaining coefficients had p-values ≤ 0.05 . At each step, the variable with the highest p-value was chosen for elimination until the stop criterion was met. While not eliminating the difficulties inherent in the relatively small sample size and high dimensionality of the data, this regression procedure allowed the stability of the model to improve with the removal of suspect variables. These procedures concluded with the two models summarized in Table 4.

Table 4. Final Regression Models

Independent Variables	Client Satisfaction Model	Design Quality Model
Intercept	4.203 **	1.899 **
C/PD	0.085 **	
C/IG		
C/EA	-0.110 **	
C/DR		-0.159 **
S/PD		
S/IG		0.060 *
S/EA		
S/DR		0.117 **
D/PD	0.027 **	
D/IG		
D/EA	0.020 **	0.018 **
D/DR	-0.006 **	
R²	0.957	0.908
Standard Error	0.377	0.369
Degrees of Freedom	8	9
n	14	14

* $p \leq .05$, ** $p \leq .01$

Five design process variables are significantly associated with client satisfaction, explaining nearly 96% of the variation in client satisfaction scores. Problem definition activities at both concept and detailed levels, and detailed engineering analysis have positive associations, while engineering analysis at the concept level and design refinement at the detailed level are negatively associated with client satisfaction. The remaining variables are not statistically

significant. The model achieves excellent fit, as shown by the R^2 value of better than 0.95, with a standard error of about 0.38 on the response scale of 1-10. The residual plot is reasonable for the sample size.

The regression of design quality against activity hours terminated with four significant variables, with detailed engineering analysis again showing up as a positive factor, along with system-level idea generation and design refinement. Concept level design refinement, however, is negatively associated with the design quality measure. All other variables are not statistically significant. The model of design quality also shows an excellent fit with an R^2 better than 0.90 and a standard error of approximately 0.37 on the response scale of 1-7. Again, the residual plot shows no cause for concern.

Regressions of both quality measures including possible control variables such as semester, year, advisor, team size, hours allocated to non-design activities, and total design hours yielded inferior models to those relying on process variables alone.

DISCUSSION

While this analysis does not demonstrate causality, it does show an apparently strong relation between increased levels of effort in certain activity-design level combinations and improved (or worsened) outcome qualities. Further, there appears to be little overlap in the activities supporting the two measures of quality used. Only in the area of detailed engineering analysis does increased effort show a significant impact on both customer satisfaction and design quality. Table 5 summarizes the significant effects seen in both models.

Table 5. Directions of Significant Factors

	Customer Satisfaction				Design Quality			
	PD	IG	EA	DR	PD	IG	EA	DR
C	+		-					-
S						+		+
D	+		+	-			+	

Taken together, the results suggest that problem definition (PD) has a positive impact on customer satisfaction at both the concept and detail levels, but that system-level PD has no direct effect on either measure. In contrast, and somewhat surprisingly, idea generation (IG) appears to be significant only with regard to design quality and only when conducted at the system level, perhaps because new ideas are of limited value unless they are generated “in place” as it were, taking into account the existing framework of the design.

This last condition may be specific to novice designers, where inexperience limits their ability to separate good ideas from bad unless the representation used to generate ideas contains sufficient information on the surrounding system. Where expert designers might simply know how to “fill in the blanks” in the design, novices might need a hint, and the inclusion of references to the adjacent design elements may act as a solution-implying mechanism. By contrast, at the conceptual or detailed level, new ideas are generated in isolation from their neighbors in the design, suggesting that

these levels of abstraction may be less suited to IG where the integration of design elements is a key issue.

Not surprisingly, more hours poured into detail level engineering analysis (EA) contributes significantly to both the engineering validity of the final solution and to happier clients. In contrast, the negative response seen in the C/EA cell suggests a clear preference for engineering analysis at lower levels of abstraction, possibly because students are better trained in detailed analyses than abstract ones. Another possible explanation is that early analyses may be ineffective or even harmful when much of the design is subject to uncertainty or outright change.

Effort spent on design refinement activities (DR) shows a clear preference as well: with customer satisfaction responding negatively to D/DR, and design quality negatively associated with C/DR. To improve quality, it seems that design refinement should be focused on the level of abstraction involving interfaces within the design, as indicated by the S/DR cell.

Viewed separately, it appears that customer satisfaction is strongly dependent upon problem definition activities. This relationship suggests that customer satisfaction may involve the issue of answering the “right” problem, or developing a thorough understanding of the real problem involved. Design quality, by contrast, seems to rely more on ideation and refinement of the system-level issues involving the configuration of sub-systems and their interactions.

Table 6 shows the model coefficients in relative magnitude: all coefficients are shown as the ratio of their value in the regression model divided by the magnitude of the smallest effect (D/DR), with the design quality coefficients scaled to reflect the difference in the two measurement scales. This illustrates the relative importance of each factor to the two outcomes measures. As evident here, not only is D/DR the least important influence on customer satisfaction, but in comparison, D/PD is 4.5 times as beneficial on a per-hour basis, while C/PD is fourteen times as important as D/DR in influencing the customer satisfaction results. Surprisingly, the largest factor is negative, with C/EA having eighteen times the impact on quality that D/DR does. Design quality appears more sensitive to its fewer variables, with C/DR demonstrating a massively negative impact, and system level design refinement showing a positive impact almost as large. Within the limits of the data, Table 6 demonstrates a means of prioritizing design activities, given weights for the relative importance of client satisfaction and design quality from an engineering perspective.

Table 6. Scaled Model Coefficients

	Customer Satisfaction	Design Quality
C/PD	14.0	
C/IG		
C/EA	-18.1	
C/DR		-39.5
S/PD		
S/IG		14.9
S/EA		
S/DR		29.1
D/PD	4.5	
D/IG		
D/EA	3.4	4.5
D/DR	-1.0	

However, in applying these results, the limitations and assumptions inherent to the study are also important. First, as mentioned earlier, this linear analysis is assumed to be a local description of what experience suggests is more generally a nonlinear phenomenon. For example, with regard to customer satisfaction, C/PD appears to be the most positive factor influencing outcome. A project that does *only* conceptual problem definition, however, will likely receive a very low score for customer satisfaction. Similarly, the fact that D/DR is negatively associated with CSQ score only suggests that we minimize its presence within the limits imposed by our design goals. Despite the straightforward meaning of the regression results, we must add a clause to each variable, allowing for the fact that there are upper and lower bounds on each activity-abstraction pair, whose true value may be difficult to describe. In other words, the results are applicable only over the ranges of the variables in the sample. What the results *do* say is that if we have a straight choice between detailed and conceptual problem definition, the latter is likely to be more beneficial to pursue.

Secondly, this study is based on data describing the activities of seniors in the mechanical engineering program at Montana State University: this means that the model presented here is a description of essentially novice design efforts in an educational setting. Without further investigation, it remains to be seen whether the conclusions developed here can be generalized to industrial settings, more experienced designers, or other academic environments or disciplines.

CONCLUSIONS

Perhaps the most compelling conclusion from the results of this analysis is, process matters. In fact, it matters a great deal, perhaps more than we realize. In the final models, we included no control variables such as ethnic or gender diversity, team cohesiveness (or lack thereof), personality types, learning styles, academic background of the students, how involved the client was, advising style of the faculty advisor, team effort, nor any other variable that might affect the team’s ability to achieve a successful outcome. We had diversity in the sample along all of these dimensions, yet even without modeling these factors, we can explain over 90% of the variability in the outcomes measures strictly from design

process variables. It appears that the impacts of team diversity, personality types, etc. are important only to the extent that they contribute to or detract from an optimal design process.

A second conclusion is, how you measure the “goodness” of the design outcome also matters. We had weak correlation between design quality as perceived by practicing professional engineers, and client satisfaction with the end product. Further, the process variables that were significantly associated with the two outcomes measures overlapped in just one variable (detail level engineering analysis). This suggests that design processes that lead to client satisfaction look different than processes that lead to strong engineering solutions. Design processes can be tailored to achieve different outcomes, and a “good” design process depends heavily on what you use to measure the quality of the final outcome.

Finally, the regression analysis suggests that all design activities are not equal. Some contribute more heavily to client satisfaction or design quality, and can have positive or negative impacts. Specifically, problem definition activity contributes strongly to client satisfaction whereas concept-level engineering analysis strongly detracts from it. Also, system-level idea generation and design refinement are strongly positive contributors to design quality, whereas design refinement at the concept-level is a strong negative contributor. Thus, these results suggest that design educators would be wise to encourage their design students to spend adequate time in activities associated with problem definition (understanding client requirements, defining constraints, information gathering on unfamiliar technology, etc.) and generating and refining system architectures associated with initial conceptual designs. They would also be wise to advise students to avoid too much time analyzing or refining conceptual ideas—it appears much better to spend that time fleshing out the ideas and analyzing them at higher levels of resolution.

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REFERENCES

- [1] Birmingham, R., Cleland, G., Driver, R., and Maffin, D., 1999, *Understanding Engineering Design: Context, Theory, and Practice*, Prentice Hall Europe, Hertfordshire.
- [2] Haik, Y., 2003, *Engineering Design Process*, Brooks/Cole, Pacific Grove, California.
- [3] Otto, K. N., and Wood, K. L., 2001, *Product Design*, Prentice Hall, Upper Saddle River, New Jersey.
- [4] Pahl, G. and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer, London.
- [5] Ullman, D.G., 2003, *The Mechanical Design Process*, McGraw-Hill, New York.
- [6] Jain, V. K., 2003, “*Relating Design Process to Design Outcomes in Engineering Capstone Projects*,” M.S. thesis, Montana State University, Bozeman, Montana.
- [7] Johnson, E. W., 1996, “*Analysis and Refinement of Iterative Design Processes*”: PhD thesis, University of Notre Dame.
- [8] Brockman, J. B., 1996, “*Evaluation of Student Design Processes*,” Frontiers in Education Conference, Salt Lake City, Utah.
- [9] Waldron, M., and Waldron, K., 1992, *Mechanical Design: Theory and Methodology*, Springer-Verlag, New York.
- [10] Ericsson, K. A. and Simon, H. A., 1984, *Protocol Analysis*, MIT Press, Cambridge.
- [11] Atman, C. J., Bursic, K. M. and Lozito, S. L., 1996, “*Application of Protocol Analysis to the Engineering Design Process*,” ASEE Annual Conference Proceedings.
- [12] Sobek II, D.K., 2002, “*Preliminary Findings from Coding Student Design Journals*,” 2002 American Society of Engineering Education conference, Montreal, Canada.
- [13] Sobek, D. K., 2002, “*Use of Journals to Evaluate Student Design Processes*,” 2002 American Society of Engineering Education conference, Montreal, Canada.
- [14] Brackin, M. P., and Gibson, J. D., 2002, “*Methods of Assessing Student Learning in Capstone Design Projects with Industry: A Five Year Review*,” ASEE Annual Conference Proceedings.
- [15] Lewis, W.P. and Bonollo, E., 2002, “*An analysis of professional skills in design: implications for education and research*”, *Design Studies*, **23**(4): 385-406.
- [16] Shelnutt, Buch, Muffo, and Beasley, 1997, “*Capstone Experience Draft Assessment Instruments*” Prepared by a subgroup of SUCCEED's Outcome Assessment Focus Team.
- [17] Saaty, T. L., 1980, *The Analytic Hierarchy Process*, McGraw Hill.
- [18] Santos, J. R., 1999, “*Cronbach's Alpha: A Tool for Assessing the Reliability of Scales*”, *Journal of Extension*, **37**(2).
- [19] Sobek, II, D.K. and Jain, V.K., 2004, “*Two Instruments for Assessing Design Outcomes of Capstone Projects*,” to appear in the Proceedings of the 2004 American Society of Engineering Education Conference, Salt Lake City
- [20] Weisberg, S., 1985, *Applied Linear Regression*, John Wiley & Sons, New York.