Two Instruments for Assessing Design Outcomes of Capstone Projects

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Abstract

A "good" design process is perhaps best defined by its output—good design processes produce good design outcomes. As part of an NSF-funded research effort to better understand student design processes, we developed two assessment instruments to measure the "goodness" of a design outcome. This paper describes the development and validation of the two instruments, presents the instruments and their implementation, and reports validation statistics on the initial data collected.

1. Introduction

A common goal of many engineering design capstone courses in the US and elsewhere is to teach the students a "good" design process. In fact, many course instructors evaluate student design teams in these courses primarily by how well they define and/or follow a prescribed process. The underlying assumption is that good design processes lead to good design outcomes—but is that true? And if so, how can we know whether a design process is good? We propose that the goodness of a design process should be measured by the quality of its outcomes. As part of a larger to study to better understand student engineering design processes, we needed a way to measure design outcomes.

Development and successful implementation of a versatile capstone course assessment and evaluation system is potentially useful. Lack of effective assessment and evaluation tools can lead to false or inaccurate conclusions about the goodness of design processes. Yet, considering the ubiquitous presence of capstone design courses in almost every engineering curriculum, outcomes assessment of these courses is perhaps among the most under-researched topics in engineering education.

Cost, time and quality are the three basic performance measures attached to any process. In the capstone design projects we studied, *time* can measured in terms of number of weeks of total design time, e.g., one 15-week semester. The *cost* can be measured by the number of person hours devoted to the project. This paper, however, focuses on *quality* measurement, specifically the development of two distinct instruments designed to measure the quality of a design outcome, the Client Satisfaction Questionnaire (CSQ) and the Design Quality Rubric (DQR).

After a review of the common assessment strategies currently in use for senior capstone courses, the ensuing sections review the development, validation and data collection of the two instruments. We conclude by presenting some of the data collected in the initial implementation of the two instruments.

2. Design Assessment in Academia

To better understand the current state of design assessment in engineering education, we first conducted an exhaustive search of six prominent journals and a number of conference proceedings. To our surprise, we turned up no quality evaluation rubrics, and only a handful of articles on customer satisfaction measurement.[1-5] Unfortunately, none of these were directly suitable for our purposes. Most of those found were either qualitative in nature which did not suit our need for a quantitative measurement, or were focused on process characteristics whereas we wanted an outcomes assessment that was independent of the process used to achieve that outcome.

Having found little in the literature on this topic, we then contacted numerous mechanical engineering capstone instructors around the US. We received some 30 evaluation rubrics for senior capstone projects, and about six client satisfaction surveys. We also looked up the design evaluation criteria for eight national engineering design contests.

These data indicate that typically instructors base their senior design project assessment on some combination of: written final reports, final presentations, interim reports/presentations, quizzes, prototypes, peer evaluation, design journals/notebooks, or evaluator judgment. Interestingly, these data strongly indicate that capstone instructors typically do not evaluate design deliverables on design quality directly; rather, students are evaluated based on process (aside from criteria like technical writing and professionalism). For example, in some of the programs we contacted, students would receive a higher score if they performed and design-for-manufacturability analysis (process), not based on how easily their design could be manufactured (outcome). Note the following typical criteria from three institutions:

> "Clear and well thought out Design Process" (Purdue University)
>
> "Identification of alternative designs, and analyzing them from many different perspectives: e.g., economic; health and safety; manufacturability; environmental; ethical; social; and legal" (University of Illinois at Urbana Champaign),
>
> "Redesign--evaluate design and revise" (Northwestern University)

Increasingly, engineering curricula are being pushed to evaluate the quality of their product based on outcomes, not inputs. It appears, though, that this outcomes assessment perspective has not made many inroads into engineering design education. For instance, identification of alternative designs, and analyzing them from many different perspectives, doesn't necessarily mean that the final design was actually a "successful" design.

Another surprising finding was that capstone assessment at most of the schools studied here excludes "client / sponsor satisfaction" as a metric in assessing the final grade, even though it is perhaps the most widely recognized performance metric in industry. Since capstone courses are often designed to simulate real world industry experience, customer satisfaction would seem essential to an effective and comprehensive outcomes evaluation system for those design capstone experiences that involve industry sponsorship.

Our goal was to develop an assessment system for capstone design projects that evaluates each project based on its outcome quality rather than the process that students used. With a process-independent measurement tool, we could then begin to analyze what design process characteristics tend to result in better design outcomes. As a result, the objectives for the design of the evaluation tools used in this study were that:

- Instruments should be free of process attributes
- Instruments should be designed considering the type of projects
- Instruments should be consistent and reliable

We now turn the discussion to the development, validation and deployment of the Customer Satisfaction Questionnaire.

3. The Customer Satisfaction Questionnaire (CSQ)

The background research described in the previous section resulted in a number of articles on measuring client satisfaction of design projects, and approximately six non-validated client satisfaction questionnaires currently in use. We developed a set of customer satisfaction metrics that incorporated the common elements across all these sources. Questions were then brainstormed or adapted from the sample surveys, and revised over several iterations.

To ensure face validity[6] of the survey—that is, whether the questions measure what they purport to measure—two research assistants critically evaluated the questionnaire from the following perspective:

1. Does each question measure what it is intended to measure?
2. Will respondents understand all the words?
3. Will all interpret all the questions similarly?
4. Does each question have answer that is applicable to each respondent in the sample?
5. Does the questionnaire create a positive impression – one that motivates people to answer it?

As a result of this exercise, we modified several questions that were not quite applicable to the intended measurement.

To ensure content validity, [6] four MSU faculty members evaluated the questionnaire with the same questions in mind. Since all four serve as a faculty advisors on student design projects and two have been past project sponsors / clients, they were well-positioned to evaluate the content of the individual survey items. The questionnaire was again revised based on the reviewers' feedback.

The final questionnaire was composed of 20 questions, 18 of which focused on the six metrics reported in Table 1. A five-point Likert scale is used for most questions. The scales for a few questions were reversed to crosscheck the integrity of the responses. Yes/No questions were coded 1 = No and 5 = Yes. Two questions are descriptive. A simple coding scheme was developed to quantify the responses on a five-point scale. For the question on client's role in the meetings with the students, we created a scale based on the level or degree of mentoring. For the question on the accuracy and completeness of the final prototype (if any), we coded the clients' responses as "good" (5), "medium" (3), or "bad" (1). The survey is designed to be finished in a period of 10 – 12 minutes. A copy of the survey is attached as an appendix.

We then used the analytic hierarchy process (AHP) to establish weights for combining the different measures. AHP is a systematic method for evaluating alternatives along multiple criteria, and results in a set of normalized weights for each criterion within a category.[7] The weights we derived for the set of measures are reported in Table 1. The consistency ratio (CR) was calculated for each measure, and all were acceptable (i.e., < 0.10). See Jain[8] for a complete description of the AHP procedure used.

TABLE 1: CLIENT SATISFACTION METRICS AND WEIGHTINGS

Metrics	Survey Questions	Weight	CR
Quality	Approximately what percentage of the design objectives do you think the design team achieved?	0.7500	.00
	On a scale of 1 – 5, how close was the final outcome to your initial expectations?	0.2500	
Cost-Benefit	How much did your company benefit as a direct or indirect result of the design project outcome?	0.6200	.08
	If no, then how much potential do you think the design holds to bring any potential benefit for your company?	0.2900	
Involvement	Approximately how often did you meet the design team or with its representatives?	0.2741	.04
	Approximately how often did you communicate with the students other than the above-mentioned meetings?	0.1094	
	How would you rate the quality of communication between the design team and you during the project?	0.4960	
	What was your role in these meetings / communications?	0.1203	
Complexity	How would you rate the technical difficulty of the design problem assigned to the design team?	NA	NA
Deliverables	Accuracy and completeness of the final report	0.5879	.06
	Accuracy and completeness of the final presentation	0.0792	
	Quality of the engineering drawings	0.2201	
	Accuracy and completeness of the final prototype	0.1126	
Overall	How feasible is the design in its application and fabrication?	0.1650	.04
	Are you going to implement this design?	0.1650	
	How would you rate your overall satisfaction with this design outcome?	0.0447	
	How well do you think the students on this team were able to apply their knowledge of math, science and engineering in the solution of problems and developing the designs? (Thoroughness)	0.6251	

To collect the client responses, we contacted the clients to set up a phone appointment. We then faxed a copy of the survey to them in advance of the telephone interview. During the telephone interview, the research assistant walked through the survey questions, and recorded the oral responses of client. This approach gave us a response rate of 100% on the 14 projects surveyed.

Not all clients were able to answer all the questions. For example, a client cannot assess the quality of the engineering drawings if he did not look at them. Since missing data can seriously affect results, we recalculated the AHP weights for each questionnaire with a missing value (see Jain[8] for details). This enabled us to get a value from each client for each of the six measures.

After collecting data from 14 projects' clients, we analyzed it for internal consistency (or reliability) using Cronbach's alpha coefficient. A high alpha value (closer to 1) indicates high intercorrelation, while a low value (closer to 0) indicates low intercorrelation. Generally, an alpha value greater that 0.6 indicates that combining the measures is acceptable.[9] As Table 2 shows, the "Quality" and "Overall" metric have acceptable coefficients of 0.78 and 0.70 respectively. The low coefficients on the other metrics implied that those metrics could not be combined to obtain a single composite score.

TABLE 2: CRONBACH'S ALPHAS (WITHIN METRICS)

Metric	**Alpha**
Quality	0.78
Cost	0.07
Deliverables	0.50
Overall	0.70
Involvement	0.38
Complexity	NA

The next step was to analyze the Cronbach's coefficients alpha across the metrics for the questionnaire. Table 3 shows that there is a fairly high consistency between the "Quality and the "Overall" metrics (0.87). However, the other coefficients are very low. Thus, the final client satisfaction score is obtained by combining the Quality and the Overall metrics only. The scores on the other metrics were discarded because they failed the reliability analysis.

TABLE 3: CRONBACH'S ALPHAS (ACROSS METRICS)

	Quality	**Cost**	**Deliverables**	**Overall**	**Involvement**	**Complexity**
Quality	1.00					
Cost	0.01	1.00				
Deliverables	0.00	0.00	1.00			
Overall	0.87	0.16	0.00	1.00		
Involvement	0.00	0.00	0.45	0.00	1.00	
Complexity	0.00	0.03	0.45	0.00	0.58	1.00

4. Design Quality Rubric (DQR)

Client satisfaction is clearly an important measure of design quality. However, client sponsors of student projects come into the venture with different expectation levels, and satisfaction is relative to these expectations. In fact, during many of the telephone interviews with clients, they often responded, "They did a good job…for students." This lead to us to develop a more objective measure of design quality, one composed of certain central and universally applicable metrics. Each project would be evaluated against the rubric by a practicing professional engineer. The idea was to focus more on the result of a design project and not on the process chosen to attain those results.

The first step was to develop the metrics. We first developed a comprehensive list of some 23 metrics from the evaluation schemes collected from the various universities and design competitions mentioned in Section 2. Since many of the metrics were similar (e.g., creativity and innovation) or related, and we were able to combine the metrics into the six categories listed in Table 4.

TABLE 4: DESIGN QUALITY METRICS

Metric	Surrogate
Requirements	Functionality
Feasibility	Manufacturability, Marketability, Application
Creativity	Originality, Novelty, Innovation
Simplicity	Reliability, Serviceability, Practicality, Ergonomics, Safety
Aesthetics	Packaging, Style
Professionalism	Workmanship, Craftsmanship, Technical Excellence

We then created a checklist to determine how well the combined metrics mapped back to the original sources. Aesthetics and Professionalism scored the lowest, with only 19% and 23% of the sources evaluating along these measures respectively. In addition, we recognized that aesthetics and craftsmanship/worksmanship are not important criteria in many of the student projects at Montana State University. We thus decided to create an "overall impression" category where the reviewer could take into account aesthetics, technical excellence, etc. as applicable to each project. A short definition was developed for each metric to help ensure correct and consistent interpretation by all evaluators. Table 5 contains the final metrics and definitions.

A seven-point scale was used for each question/metric and three anchors were provided ("Poor" being 1, "Acceptable" being 4 and "Outstanding" being 7). A brief rationale was requested from each evaluator on each response for the purpose of inter-reviewer comparisons and to help validate consistency among the evaluators. Refer to the Appendix for a copy of the actual Design Quality Rubric.

TABLE 5: DESIGN QUALITY MEASURES

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

For implementation purposes, four engineering professionals were hired to evaluate the design projects. Three of these evaluators were professional mechanical engineers with over 10 years of experience in design/manufacturing. The fourth had 5 years of mechanical engineering experience and had applied for his professional license at the time of the study. These evaluators were asked to evaluate the projects' outcomes as if they were evaluating actual industry designs, and given the project time and budget constraints. They were given specific instructions to assess the design projects on their outcomes and not on the process used to achieve that outcome.

The final reports of each project served as the means for evaluation. Each evaluator was assigned reports in such a way that each report was evaluated twice and each evaluator evaluated at least six reports to provide redundancy in the measurement. The final result was obtained by averaging the scores on individual metrics across reviewers. There were no missing values in the data collected.

5. Results

Tables 6 and 7 display the results obtained for the Client Satisfaction Questionnaire (CSQ) and the Design Quality Rubric (DQR) for 14 projects. The values in Table 7 are averages of the evaluator scores. The final score is the mean of the five metrics.

The next step was to examine if the CSQ and the DQR scores could be combined to obtain a single composite score on the design project outcome. The Cronbach's alpha coefficient of 0.52 implied that the two scores were measuring different things and could not be combined to obtain a single composite score. Also a two tailed p-value of <0.0001 indicated the two data sets come from statistically different populations and thus confirmed the Cronbach's analysis. Further, visual inspection of a x-y plot showed no strong correlation trends between the two scores. This likely reflects the fact that quite a number of clients for these projects did not have engineering backgrounds, and that they were possibly looking for more than an engineering solution.

TABLE 6: CSQ SCORES PER PROJECT

Project	Quality	Overall	Final Score (Quality + Overall)

A	4.75	4.34	9.09
B	4.75	4.50	9.25
C	4.75	4.79	9.54
D	5.00	4.63	9.63
E	4.00	3.17	7.17
F	4.50	3.67	8.17
G	4.75	4.34	9.09
H	4.50	4.01	8.51
I	4.00	3.68	7.68
J	2.75	3.38	6.13
K	3.00	2.38	5.38
L	3.00	3.68	6.68
M	4.75	4.17	8.92
N	3.75	2.43	6.18
Mean	4.16	3.80	7.96
Std. Dev.	0.76	0.76	1.42

TABLE 7: DQR SCORES PER PROJECT

Project	**Requirements** Scale: 1-7	**Feasibility** Scale: 1-7	**Creativity** Scale: 1-7	**Simplicity** Scale: 1-7	**Overall** Scale: 1-7	**Final Score**
A	6.00	5.00	5.00	5.50	5.00	5.30
B	4.67	5.67	6.00	4.67	5.33	5.27
C	5.00	4.00	3.00	5.00	4.00	4.20
D	6.00	5.50	4.50	5.00	5.00	5.20
E	3.00	5.00	3.50	5.00	3.50	4.00
F	4.50	4.00	3.50	4.50	3.50	4.00
G	5.50	4.50	4.00	5.50	4.50	4.80
H	5.50	5.00	5.50	5.50	5.50	5.40
I	3.00	3.50	4.00	2.50	3.00	3.20
J	4.00	4.00	6.00	5.00	5.00	4.80
K	1.00	1.00	5.00	1.00	1.00	1.80
L	3.50	4.50	4.50	4.00	3.50	4.00
M	3.00	2.00	6.00	3.50	3.00	3.50
N	4.25	5.25	4.25	6.00	5.00	4.95
Mean	4.21	4.21	4.63	4.48	4.06	4.32
Std. Dev.	1.41	1.32	0.99	1.35	1.24	1.01

6. Conclusion

Despite the clear benefits of being able to measure the quality of design outcomes, we found little prior work in this area. As a result, we developed to instruments to measure design outcomes. The first is a client satisfaction survey that was developed from the literature and actual questionnaires in use, and was validated for face and content validity. The second is a design quality rubric used by practicing engineers to evaluate student projects in light of professional engineering expectations. It was developed by amalgamating evaluation criteria from over two dozen mechanical engineering programs around the US, and distilling them down to five key metrics.

Data were collected on 14 projects. We found that only two of the six client satisfaction metrics met the internal consistency criterion, so our client satisfaction score is based on a total of six questions (two for the "quality" metric, and four for the "overall" metric). However, every institution is different, and other course instructors could follow the same procedure and find that a different set of metrics works better for their projects. In addition, different programs may face different challenges in assessing design outcomes. For example, client satisfaction may have little meaning in a capstone course where projects are not industry sponsored. Such programs may have to think differently about how to assess their design outcomes. An alternative approach might be to use a House of Quality or similar tool that directly maps engineering specifications onto user needs. Such an approach could be easily adapted to provide quantitative assessments of how well the technical specifications serve to delight the user.

Finally, we found that we obtained significantly different scores using the two instruments. Thus, the CSQ and DQR scores should not be combined: customer satisfaction and design quality should kept as separate measures of capstone project outcomes where such measures are applicable.

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Appendix:
Customer Satisfaction Questionnaire

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[1] What were the design objectives for the project? What did you expect the team to accomplish?

[2] Approximately what percentage of the design objectives do you think the design team achieved? _____ %

[3] On a scale of 1 – 5, how close was the final outcome to your initial expectations?

1	2	3	4	5
Significantly Below		Met		Significantly Above

[4] Did you establish a budget for the design project? ☐Yes ☐ No (If NO, go to Q # 5)
If yes, did the project meet this budget? ☐Yes ☐ No (If YES, go to Q # 5)
If no, was this extra cost justified? ☐Yes ☐ No

[5] How much did your company benefit as a direct or indirect result of the design project outcome?

1	2	3	4	5
No Benefit		Benefited Somewhat		Benefited a great deal

[6] If you answered 1, 2 or 3 to question 5, how much potential do you think the design holds to benefit your company?

1	2	3	4	5
Little, if any		Moderate Potential		Excellent Potential

[7] Approximately how often did you meet with the design team over the course of the semester (face-to-face)?

☐ 0 Times ☐ 1 – 2 Times ☐ 3 – 6 Times ☐ 7 – 12 Times ☐ > 12 Times

[8] Approximately how often did you communicate with the students other than the above-mentioned meetings? (E.g. e-mail, phone conversation, etc…)

☐ Multiple Times Daily ☐ Daily ☐ 1 – 2 Times / Week ☐ 1 – 2 Times / Month ☐ < 1 time / Month

[9] How would you rate the quality of communication between the design team and you during the project?

1	2	3	4	5
Highly Productive		Moderately Productive		Waste-of-time

[10] What was your role in these meetings / communications?

[11] How would you rate the technical difficulty of the design problem assigned to the design team?

1	2	3	4	5
Extremely Easy		A Little Difficult		Extremely Difficult

[12] Did you review the final report? ☐ Yes ☐ No (If NO, go to Q # 13)

If yes, how accurate was the final report?

☐ Very Accurate ☐ Mostly Accurate But w/ Some Minor Errors ☐ Fairly Accurate But No Major Errors ☐ Had 1-2 Major Errors ☐ Had Numerous Major Errors

If yes, how complete was the final report?

☐ Very Complete ☐ Complete But Some Key Issues Not Addressed Fully ☐ Many Key Issues Not Addressed Fully ☐ 1-2 Key Issues Missing ☐ Several Key Issues Missing

[13] Did you attend or view a videotape of the final presentation? ☐ Yes ☐ No **(If NO go to Q # 14)**

If yes, how accurate was the final presentation?

☐ Very Accurate ☐ Mostly Accurate But w/ Some Minor Errors ☐ Fairly Accurate But No Major Errors ☐ Had 1-2 Major Errors ☐ Had Numerous Major Errors

If yes, how complete was the final presentation?

☐ Very Complete ☐ Complete But Some Key Issues Not Addressed Fully ☐ Many Key Issues Not Addressed Fully ☐ 1-2 Key Issues Missing ☐ Several Key Issues Missing

[14] Did you review the final engineering drawings? ☐ Yes ☐ No **(If NO go to Q # 15)**

If yes, how would you rate the quality of the final drawings in terms of their usability to build / manufacture the design?

1	**2**	**3**	**4**	**5**
Very Accurate & Complete		Some Inaccuracies / Missing Information		Not Buildable W/ o Major Corrections or Additions

[15] Please comment on the accuracy, completeness and quality of the final prototype.

[16] How feasible is the design in its application and fabrication?

1	**2**	**3**	**4**	**5**
Not Feasible		Fairly Feasible		Demonstrated Feasibility

Are you going to implement this design?

☐ As – Is ☐ W/ Slight Modifications ☐ W/ Major Modifications ☐ W/ Complete Redesign ☐ Probably Not

[17] **If you had a chance, would you be interested in working on another project with this design team?** ☐ Yes ☐ No

[18] How well do you think the students on this team were able to apply their knowledge of math, science and engineering in the solution of problems and the developing of designs?

1	**2**	**3**	**4**	**5**
Excellent		Fair		Poor

[19] How would you rate your overall satisfaction with this design outcome?

1	**2**	**3**	**4**	**5**
Very Satisfied		Somewhat Satisfied		Very Dissatisfied

[20] What would you do differently if you work on another student project?

DESIGN QUALITY RUBRIC

Evaluator: ______________________ Project: _________________________

Date: __________________________

	Metric	Definition	Score (1: Poor, 4: Acceptable, 7: Outstanding)	Evaluator's Rationale
Basic	Requirement s	The design meets the technical criteria and the customer requirements	☐ ☐ ☐ ☐ ☐ ☐ ☐ 1 2 3 4 5 6 7	
	Feasibility	The design is feasible in its application and fabrication / assembly	☐ ☐ ☐ ☐ ☐ ☐ ☐ 1 2 3 4 5 6 7	
Advanced	Creativity	The design incorporates original and novel ideas, non-intuitive approaches or innovative solutions	☐ ☐ ☐ ☐ ☐ ☐ ☐ 1 2 3 4 5 6 7	
	Simplicity	The design is simple, avoiding any unnecessary sophistication and complexity, and hence is: - Practical - Usable - Reliable - Ergonomic - Serviceable - Safe	☐ ☐ ☐ ☐ ☐ ☐ ☐ 1 2 3 4 5 6 7	
Overall	Overall impression of the design solution ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 1: Far Below Professionaly Acceptable work; 4: On Par With Professional Expectations; 7: Outstanding by Professional Standards			