Understanding Engineering Design As an Argumentative Strategy

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Abstract

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process . . . in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. . . . it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact. (ABET)

Introduction

One of the defining characteristics of design is that there is rarely a single correct answer to an engineering problem but, rather, an optimal or acceptable solution, a final design, presented as the best possible balance between technical as well as non-technical constraints. These non-technical constraints typically involve economics, politics, social issues, and ethics. And while professional practitioners generally accept this understanding of design, laypersons and students alike tend to interpret the engineering design process as an unambiguous and clearly defined process undergirded by rigidly applied principles and processes of "the scientific method." Bucciarelli presents engineering design for what it really is: a dynamic and highly variable creative process that produces not *the one perfect solution* to posed problems and challenges, but *a solution* (technology) that has been accepted by the design community as the best solution among several possibilities. Further, engineering design problems are solved not only through technical analysis, but also through a rhetorical process of understanding and negotiating the context in which the design will be used and the reception of the design by the various audiences

involved. Therefore, to "sell" a design is to argue persuasively with the intended audience(s) such that the design is approved and accepted. Understanding the design process as a discipline-specific argumentative discourse strategy can help us to improve engineering education and to graduate more rhetorically aware engineers from our programs. Importantly, these possibilities align well with ABET's criteria for student learning outcomes.

Background

In the spring of 2001, the NMSU College of Engineering underwent review under the criteria established by EC 2000. In the Final Statement of the ABET report to the college, the following program *concern* was noted for the Civil, Agricultural, and Geological Engineering (CAGE) Department under Criterion 3.g., "Ability to Communication Effectively":

> "The curriculum may not provide enough emphasis on the attainment of oral and written communication skills. Very little evidence is available that the students have completed written project reports. As an example, no written preliminary or final reports, such as required in outside employment, were evident from a review of the capstone design courses. Oral communication skills were not documented in the course materials. Survey results verify this concern." (10)

A program *concern* "indicates that a criterion is currently satisfied; however, the potential exists for this situation to change in [the] near future such that the criterion may not be satisfied. Therefore, positive action is required to ensure continued full compliance with the criteria" (Final Statement, 2). The reviewers' concern about the degree of emphasis on oral and written communication skills is supported by the CAGE Department's internal alumni survey results in which responses indicate a gap between "importance at work" and "preparation at NMSU" for oral, written, and interpersonal communication skills, a finding that is not uncommonly reported in the literature on engineering education.

Description of the Project

Several strategies have been suggested to strengthen compliance with Criterion 3.g., including the project described here. Specifically, we developed instructional materials for the senior capstone design seminar in the CAGE Department's environmental engineering program (ENVE 456) to help student design teams understand the rhetorical nature of engineering design and how to persuasively present their work to their clients both in written reports and in oral presentations. This work resulted in two evaluation rubrics that were used by faculty and consulting professional engineers to evaluate the strength of the design solutions developed by the student teams. A preliminary version of the evaluation rubrics were developed and piloted in the Spring of 2004.

Throughout the Spring 2004 semester, students enrolled in ENVE 456 study, analyze, and develop design solutions to a specific engineering problem that has been identified by a local engineering consulting firm. For the spring 2004 seminar, the students studied an environmental problem associated with New Mexico's colonias. Colonias are defined as rural neighborhoods and unincorporated subdivisions in or near cities along the U.S.-Mexico border, characterized by substandard housing and inadequate sewage disposal, roads, and access to clean water. The

project addressed by the Spring 2004 ENVE 456 students concerned a newly implemented wastewater system for one of these communities. The students were first guided toward a complex understanding of the system including the technical challenges and constraints as well as the economics, environmental and regulatory concerns, and social issues that impacted the design decision. A team of two engineers from the consulting firm, including the individual who designed the implemented system, critiqued the students' work at midterm in a Preliminary Engineering Report (PER) and at the end of the semester in a Final Engineering Report (FER). At each interval, the student team provided an oral presentation and a written report. Michele Auzenne, the writing specialist for the project, observed the oral presentation of the PER delivered to the consultants in April 2004. Following the PER, she then worked with Adrian Hanson and Ricardo Jacquez to develop evaluation rubrics for both oral and written engineering documentation, and instructed ENVE 456 students on the rhetorical concerns associated with engineering design. Because the rubrics and instructional materials are ultimately intended to work across all undergraduate levels within the design sequence, we also piloted the rubric for written documentation with a freshman design course. Ultimately, the rubrics and instructional materials will be used in the freshman, sophomore, junior, and senior design seminars (SMET 102, CE 256, CE 356, and ENVE 456).

Analysis of the Spring 2004 Design Presentation

In observing the student team's PER oral presentation, which was delivered to the consultants with a PowerPoint presentation, the writing specialist mistakenly assumed that the consultants in attendance were the audience for the presentation. However, as we moved on to the conversation and critique portion of the session, she realized the true audience was the community of the colonia, made clear when the question of audience was raised by one of the consultants. With this made explicit, the consultants slipped into this audience role quite effortlessly and went on to offer their critique, slide by slide, of how effective the presentation was with their intended audience. The highly rhetorical nature of the critique was quite interesting. The technical content of the presentation was discussed only occasionally; the bulk of the conversation focused on rhetorical concerns of audience, purpose, and context.

It was clear that the students did not have a good understanding of who they were to address as their audience. They had concentrated on the technical nature of their work, assuming that the consultants would be more likely to critique them on such points. However, because the consultants were not the targeted audience of the presentation, the argument did not meet the expectations of the intended audience, whose values are rooted in a history of opposition to outsiders, a sense of self-sufficiency, low income levels, and a general suspicion of the need for implementing (and paying for) a new technology. The audience was specific (the community of the colonia); however, the students had constructed and wrongly invoked a somewhat generic audience of "engineers" very much like themselves, differing only in expertise and experience. Thus, the students focused on the technical competence of their work to the exclusion of its socially grounded application and the rhetorical nature of their work in persuading the community to support and implement their design solution.

Crosswhite's theory of audience is useful here for developing an understanding of the communication taking place in this particular context. Applying Crosswhite's theory, we can

see that the students missed the "event" of audience – the situatedness of the work they were presenting and the ways in which their audience would measure the worth of their argument. It was interesting, however, that the students attempted to appeal to a "quality of life" issue – they argued early in their presentation that the proposed wastewater system would contribute to raising the quality of life in the community. But they missed the mark in that they failed to put on the value lenses of the community itself; the students' notion of quality of life did not necessarily match that of their specific audience – at least as those values were interpreted by the consultants, who had, in fact, delivered an actual presentation to the community. Audience, then, as a way of being and as a "targeted" site of communication, was deferred several times, adding further complexity to the rhetorical situation.

To address their audiences effectively, the students must learn to research their audience, and then to listen and observe as well as speak, and to be highly sensitive and responsive to the on-going act of communication and reception that is occurring. Thus, a primary focus of the instructional materials is to help students understand the complexity of audience and how to balance these rhetorical concerns with those of the technical concerns. The challenge was to present these important ideas to an audience of engineering students in a manner that would be clear and reasonably but not impossibly challenging for them to implement and practice. To do so required us to reason with the students through evidence that is meaningful to them, and to open to them new ways of understanding the issues and relationships of communication and engineering design. To begin this process, we turned to the primary definition of engineering design as a problem solving process.

Developing Solution
Problem Solving in Engineering

Engineers solve problems. In the context of engineering design, these problems can be quite complex and relatively open-ended. These types of problems can be understood as "complex" problems. On the other hand, we find what can be called "simple" problems, which are very familiar to engineering students (Robinson 1998). Simple problems are here defined as those where constraints and criteria for evaluating solutions are qualitatively similar and the explanatory framework is deductive. For example, most coursework and homework problems focus on engineering analysis and analytic skills. They generally have one acceptable answer, and can therefore be understood as "simple" in nature. However, students may be asked to define basic assumptions and interpret criteria, rhetorical acts that impact their problem solving process and ultimate solution.

Compound problems, on the other hand, are those in which evaluation criteria are not qualitatively similar and cannot be jointly optimized and where a balance must be achieved between such dissimilar factors as cost, safety and aesthetics. Additionally, some criteria may be implicit but immeasurable – for example, a "lower limit on ugliness" (Robinson). Students do not receive the same degree of exposure to these compound problems during their educational programs; however, the professional practice of engineering is largely focused on solving just this type of problem. One common feature of compound problem solving that new engineers find difficult, for example, is the need to negotiate multiple and conflicting client needs.

Viewing engineering problems in this manner sheds light on the typical complaints of engineering employers who claim that newly graduated engineers lack the communication and creative skills required to function at a high level within this type of problem situation (for example, see Katz, Sageev and Romanowski, Evans et. al., and Knox et. al.). Rhetorical skills are clearly required to resolve compound problems, where the tradeoffs involved in the final design require interpretation, justification, and support. Typically, such compound problems are broken down into several simple problems. In this case, engineers must be able to argue for the specific way in which the problem set has been arranged; i.e., why was the compound problem disaggregated into this particular array of simple problems? Yet it is important to remember that even simple problems can require a degree of rhetorical skills – particularly skills of persuasion – when the problem requires that the student or engineer determine basic assumptions. In this case, the solution derived must still be shown to be the best based on the assumptions and criteria established in the problem definition.

Woods discusses the process of solving both simple and complex types of engineering problems. In his 2000 article, he reviews over 150 published problem-solving strategies, distinguishing between "basic," and "nested" strategies and between "exercise solving" and "problem solving." Here, he defines basic strategies as single-level processes, whereas the term "nested" refers to a multi-level strategy. The distinctions in problem solving processes/approaches made here are clearly similar to and complementary to those made by Robinson when discussing problem type. Woods provides further elaboration on problem solving and the connection to problem type as follows:

> In exercise solving [simple], we retrieve a plan that was used in the past. Here, we rely on pattern recognition and matching the current problem situation to other past situations that were similar. In problem solving [complex], we must create a plan. There are no immediate connections to previous problem situations. We tend to work backwards from the goal toward the given inputs. Other terms used . . . include "productive and ill-defined" and "atypical" (pg. 444).

Here, the connections between engineering problem solving and rhetoric are clear. In fact, in exploring whether "there is anything distinctive about engineering thinking," Robinson places rhetoric – and more specifically the use of analogy – squarely at the center of engineering activity. Robinson argues that engineering has a rhetoric, a mode of argumentation, to explain its activities and to justify its decisions. Practicing engineers, he states, "probably make use of analogy as often as practicing lawyers" (228).

Bucciarelli also discusses the rhetorical nature of engineering, defining what he calls "object world thinking." Object worlds designate "the domain of thought, action, and artifact within which participants in engineering design . . . move and live when working on any specific aspect, instrumental part, subsystem, or subfunction of the whole" (62). These object worlds are comprised of concrete artifacts, symbolic mathematical relationships, techniques and methods, field logbooks and other texts, personal knowledge and interpretations, and a multitude of other contextually and individually grounded elements. "Object-world thinking," then, is analogous to what is generally referred to as "expert practice" – those practices and tacit knowledge that make one expert in a given field domain or context.

The problem of expert practice, of course, is that the closer one gets to this level of expertise, the less one is able to articulate what he or she actually *does* – practice becomes increasingly naturalized. Bucciarelli attempts to unpack the expert practice known as engineering design through a rhetorical framework of "narrative" to describe *what actually happens* throughout this process versus *what we think happens*. In other words, the engineering design process unfolds not as a predetermined linear process, but more like a narrative with various characters, situations, and subtexts all having a role in its ultimate conclusion (i.e., produced technology).

Framed by this understanding of design process as analogous to narrative, Bucciarelli discusses "the rhetoric of objects." The rhetoric of objects comprises the methods and processes of communication and persuasion that allow participants in contemporary design projects to come together and negotiate their various responsibilities and interests to produce a final product. Given the variety and degree of specialization that characterizes contemporary engineering design (i.e., the number of unique object-worlds, which may be grounded in multiple companies and/or workplace environments), a sophisticated rhetoric is required to communicate effectively "across the universe." What is striking here – and what students of engineering are not often aware of – is that bringing the elements of a design together in a manner that does, in fact, communicate across such "worldly boundaries," involves far more persuasion and rhetorical skill than one might expect. For example, fundamental understandings of the relationships, constraints, and intervals that engineers negotiate in the design process can vary considerably among team members (e.g., time can be critical in terms of seconds, hours, or days depending on the object-world in which you operate). Engineers must, therefore, be continuously involved in the business of constructing persuasive arguments that synthesize these elements and understandings, as well as those socially constructed meanings that emerge from specific workplace contexts, to present their designs convincingly, even among themselves.

Rhetoric and Communications Training in Engineering Education

The engineering literature tends to refer relegate communications and social competencies as "soft skills" (Hissey, T.W.) "performance skills" (Seat, et. al.) or, "generic skills" (Hoddinott and Young). These skills include abilities to communicate effectively and to work in teams, to be self-starters, critical thinkers, and problem solvers as well as having attitudinal characteristics such as "persistence" and "assertiveness" (Hissey) and an awareness of business finance or the economic aspects of design activity (Hissey; Knox, et. al.). These skills are clearly set apart from technical competencies, which are those traditionally taught in engineering programs. These competencies include such features as a solid technical education, the ability to think and reason logically, strong work ethics, and computer literacy (Hissey). And while there are several examples of program- or college-wide implementation of communications training (e.g., Plumb and Scott) most efforts to address such training are classroom based and encompass a wide variety of approaches including journal writing, portfolio projects, and written and oral reporting requirements. Most of these efforts have been developed and implemented as a result of the revised ABET criteria and are relatively new to the engineering curriculum despite a long pattern of recognizing that engineers have not been effectively trained in this critical area (Mair and Radovich).

While it is clear that engineering educators understand the importance of teaching engineers to communicate effectively, communication is treated as a necessary final or close-to-final step in the engineering design process. However, two articles have come to our attention that examine the relationship between communication and design in more complex ways. Odell and Swartz discuss the rhetorical nature of engineering design work and how effective practice and assessment of engineering writing can inform and support better engineering design. Ahearn, an engineer by training, takes a different approach, using rhetorical analysis to pose the question of whether engineering, in fact, has the language – words, metaphors, and themes – to effectively communicate engineering practice. A third article (Donnell, Peetraglia-Bahri, and Gable) also discusses the integrated nature of communication and engineering activity, but approaches it in yet another manner. In this case, "scribal" and "rhetorical" skills are presented as separate matters. Specifically, they wish to teach "rhetorical" skills in professional content courses and see the business of introductory writing courses as teaching "scribal" skills, which they describe as "a large body of mechanical information about writing." Their argument that discipline-specific faculty should evaluate the success with which students demonstrate these skills is one that deserves respectful consideration. Despite the strength of the recommendation, the greater majority of scholars studying engineering communication address the issue – as we have – through collaborative efforts between engineering faculty and writing specialists or English faculty.

Collectively, these articles support the notion that engineering design can be seen not only as the process by which engineers create solutions to human problems, but also as a discourse strategy that is used to facilitate and communicate those solutions. It is this more complex understanding of communication and design skills that will continue to guide our work.

Developing the First Iteration of Communication Assessment Rubrics

As a first step toward this goal, we developed two assessment rubrics – one for engineering documentation (written and oral) and one that specifically addresses the additional concerns of the oral presentation mode. The format and content of the rubrics were drawn extensively from the literature of engineering education, our own experiences as a writing instructor and engineering faculty, and the observations that were made while observing the ENVE 456 students' PER presentation to the consulting engineers. Following initial development of the rubrics and discussions with the design sequence faculty, the rubrics were presented to the ENVE 456 students. In that discussion, we focused on audience analysis and, particularly with respect to the oral presentation mode, the interaction and awareness that is required to respond effectively to the audience in the context of the presentation itself.

A primary consideration in developing the materials was to mirror, as closely as possible, the conventions and expectations of the engineering discipline. We also wanted to develop materials that could be adapted to a variety of engineering contexts and specializations. Additionally, it is clear from the literature that engineering students expect and value highly directive instruction. Providing a bridge between these expectations and the degree of creative and independent thought required of engineering design activities was a challenge. Too concrete, and the students don't think; too abstract, and they have nothing with which to make appropriate connections.

We decided to prepare one rubric for engineering documentation that would work across genres. This demanded consideration of the general concerns of engineering documentation and communication and not on issues such as formatting requirement, the use of headings and other guideposts, and the specifics of design reports vs. oral presentations or progress memos. The concern here is on the effectiveness of the communication; the professor must provide the specifics of the assignment or genre. While this allows for a broader range of use for the rubrics, there are implications for faculty development that must be considered. Faculty must be fully aware of the intent of the rubrics and of the material and direction that must be provided to the students in conjunction with the rubric. In a sense, this allows for the valuing of "good communication" over "good writing" as that term is defined in Pappas and Hendricks. In their 2000 article, "Holistic Grading in Science and Engineering," Pappas and Hendricks argue for "the values of the workplace" over those of academic writing. In the workplace, they explain, the message of the author is most important; adherence to the conventions of academic writing as those conventions tend to be taught by English departments are secondary (404). Good communication is, of course, dependent on effective language use and we can never separate the two, but the point is well taken; what works in industry is often different from what works in the English classroom. These differences are also discussed by Miller, Bausser, and Fentiman in their 1998 article, "Responding to Technical Writing in an Introductory Engineering Class: The Role of Genre and Discipline." In a case study focused on the commenting style of an engineering professor, they observe that the design report genre contains conventions that would be seen as redundant and constructions that would be discouraged by the traditional English teacher, for example, redundant explanatory material in various sections of the report and use of the passive voice.

The oral presentation rubric incorporates a four-point assessment scale, indicating the degree of success demonstrated in synthesizing the criteria and considerations of the engineering task. The criteria selected include audience, purpose, development, focus, and coherence. Each of these terms is operationalized in terms that allow the engineering students to make appropriate connections to engineering processes. For example, "development" is operationalized in terms of providing evidence that demonstrates consideration and synthesis of the identify criteria, which may include both technical and non-technical elements. These criteria must be provided by the professor in each case. To develop the content of the rubric, We relied heavily on the literature. Beginning with the model provided by Laeser, et. al., we compared the original rubric to the literature, modifying and adding content with the goal of creating a comprehensive instrument that would work across genres. For example, based on Odell and Swartz, we added considerations of consistency and attractiveness of format.

The second rubric provides for only those elements that define an oral presentation from a written document. It focuses, therefore, on the ethos and presentation skills of the speaker or team and on the quality of the presentation materials. Again, the rubric is not overly specific, but can be used for a variety of presentation contexts whether a design presentation to a community or a progress report or preliminary design review to one's supervisors. An important consideration here is the responsiveness of the presenter(s) to audience questions, again emphasizing the interactive nature of oral presentations, particularly when the presentation is aimed at persuasion. Here, we used the model provided by Laeser, et. al., to operationalize and "nest" criteria adapted from Papas and Hendricks and Fentiman and Demel.

Two additional tools were developed and tested with the ENVE 456 students, an "Audience(s) Analysis" worksheet and "The Engineer's Rhetorical Triangle." The first of these, the "Audience(s) Analysis" worksheet, facilitated the conversation about audience. As we discussed the various audiences, we stopped at intervals to allow students to make notes about the values and expectations of their audiences. The second, "The Engineer's Rhetorical Triangle," collapses every aspect of the two rubrics into the rhetorical triangle. This helped students to see, graphically, how the various elements of communication and argument work together and the specific relationships and concerns that we discussed during our conversation. we designed this visual representation quite intentionally, as the literature frequently refers to the typical engineering student's reliance on graphic data. For example, Miller, Bausser, and Fentiman find that almost half (46%) of the professor's comments are about the graphic elements of the text and that a large percentage of an engineering student's invention and prewriting activities will be in the form of graphs, tables, and diagrams.

Finally, while we did not explicitly use them during the instructional session, we also developed a weighting scale for the oral and written reports and an additional handout titled, "The Rhetorical Aims of Engineering," again relying on our analysis and synthesis of the literature.

Assessment of the Rubrics

The engineering documentation rubric (for written and oral communication) was tested in the freshman introduction to engineering design seminar. Students were asked to use the rubric to guide their preparation of a design proposal. A professor of engineering (Ricardo Jacquez), one graduate student, and the writing specialist (Michele Auzenne) reviewed the students' draft proposals using the rubric. The three of us scored the proposals independently, and then compared our scoring. In almost all cases, we were within one numeric value of each other on all factors. In all cases, a brief discussion allowed us to resolve minor differences of opinion and to collectively come to a good understanding of the proposal's strengths and weaknesses. In discussing the scoring and the expectations defined by the rubric, the students were able to articulate many of the changes that were necessary to improve their proposals. Overall, the rubric was rated effective, although it was clear that the factor labeled "Voice" in the second rubric (for oral presentations) should be moved to the first rubric.

The second oral presentation rubric was used in discussions with the freshmen class and with the ENVE 456 students and professor. While we were concerned that the rubric, which is quite text heavy, would be overwhelming and possibly confusing to the students, it was clear from their active involvement in the conversation that they saw it as helpful. They appreciated a clear picture of the professor's expectations, and viewed the rubric almost as a set of directions. What was perhaps most interesting, or most rewarding, is that the students did, in fact, understand a great deal about their primary audience; they were able to articulate their values and expectations quite clearly at this point. However, it was also clear that they had never been provided with a framework through which to document, consider, and incorporate these values and expectations. Providing them with the language and tools to effectively consider audience is particularly effective in this type of problem situation, where multiple audiences and potentially conflicting values are at work. For example, the professor for the seminar (Adrian Hanson) brought to their

attention that in addition to the community, the consultants, and himself, the students needed to be aware of the audience of regulators who must ultimately approve their design solution and who had the authority to shut down implementation of the solution to the community problem if it didn't meet the regulators needs as well. Hanson also provided them with what he believes is an appropriate universal audience – their mothers. While this may appear peculiar at first glance, he explained that he tried to treat every audience as he would treat his mother – with respect and understanding for her intelligence and level of knowledge about the subject matter, and with the clear intent of helping her to truly understand what he was presenting to her. The students immediately made the important connections!

The "Engineer's Rhetorical Triangle" and "Audience Analysis" worksheet were also helpful. In particular, the visual representation of the rubrics in the rhetorical triangle seemed to clearly help students to understand the rubrics themselves. It also facilitated a discussion of context, which led to further discussion of audience concerns. The students were actively engaged in the conversation, which continued for almost a full hour.

Conclusion

Like writing, engineering design activity and communications about the products and potential impact of those activities is an iterative process that requires creative thought, flexibility, and discipline. And, like writing, the success of engineering design activity is dependent on one's ability to argue convincingly and persuasively with the intended audience. Given that there is almost never only one correct solution to a given engineering problem, it is clear that rhetorical skill is an important and central feature of successful engineering practice where, in addition to technical constraints, economics, politics, social issues, and ethics plan a role in developing solutions. Helping our engineering students to understand the process and activities of engineering design as argumentative discourse and strategy will provide them experiences that can help them to develop the necessary skills for successful practice as professional engineers. We can meet the challenges of providing such instruction in ways that are appropriate to engineering and which engineering students are likely to be receptive by giving consideration to the disciplinary expectations and the teaching and learning preferences of engineering students and faculty. It appears that we have been successful in doing this in the first iteration of the design sequence project. Yet future application and assessment of the rubrics and other instructional materials must address additional concerns: At what point in the semester should the rubrics be introduced? How frequently should the rhetorical concerns of the discipline be explicitly addressed? What additional methods for documenting real change in communication practices can be developed and implemented in the engineering classroom? How is faculty development best addressed and assessed? Will the rubrics, in fact, be useful across the various genres of engineering documentation that students will practice throughout their education? These and other questions will continue to inform our work.

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