Everyday Problem Solving in Engineering: Lessons for Educators[1]

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Many engineering programs have integrated problem-based learning (PBL) into their instruction. Quite often, the problems that are solved in PBL programs are not authentic. In order to develop more authentic problems that are required to prepare engineering graduates to solve complex, ill-structured workplace problems, we developed a case library of engineering problems as described by practicing engineers. The qualitative analysis of those stories showed that workplace problems are ill-structured because they are constrained by unpredictable, non-engineering parameters; driven by multiple, often conflicting goals; evaluated using non-engineering success criteria; possessing aggregates of smaller well-structured problems; requiring complex collaborations; and replete with unanticipated problems. The implications for developing problem-based learning environments in engineering are clear: problems must represent more complexity, ambiguity, collaboration, and dynamic conditions.

Of all of the ABET accreditation standards, undergraduate and graduate engineering students as well as practitioners consider the ability to design and conduct experiments and to identify, formulate, and solve engineering problems as being the most important [1]. In an effort to meet ABET accreditation standards and to better prepare engineering graduates, engineering education programs have been implementing a variety of forms of problem-based learning (PBL). In fact, several engineering programs around the world (e.g., Aalborg University on Denmark, McMasters University in Canada, Monash University in Australia, Manchester University in England, Glasgow University in Scotland, Eindhoven University in the Netherlands, and Republic Polytechnic in Singapore) deliver the majority of their curricula via PBL. Additionally, PBL modules or courses have been implemented in numerous engineering programs, including biomedical engineering [2], chemical engineering [3], software engineering [4,5], thermal physics [6], design processes [7], aerospace engineering [8], computing [9], microelectronics [10], construction engineering [11], control theory [12]. Limited efforts have even examined the use of PBL for engineering workplace training [13].

While PBL represents an important pedagogical innovation in engineering education, the nature of the problems that are solved by students are inconsistent with those that engineers solve in the workplace. Workplace problems are assumed to be complex and ill-structured problems because they have vaguely defined or unclear goals and unstated constraints; possess multiple solutions, solution paths, or no solutions at all; possess multiple criteria for evaluating solutions; where there is uncertainty about which rules and theories are necessary for a solution [14]. These problems often require engineers to make judgments and express personal opinions or beliefs about the problem. While engineering education programs are beginning to engage students in more authentic forms of problem solving, as evidenced by the growth of PBL programs in engineering schools, the problems that students solve tend to be well structured, even in PBL environments. If the goal of engineering education programs is to better prepare engineers for the workplace, they must introduce students to the complexities and ambiguities of workplace problems. In order to develop more authentic design methodologies for PBL programs, this study qualitatively analyzed stories of workplace problem solving in order to articulate the context, activities, and constraints that make workplace problems so ill-structured. Very few studies of workplace problem solving exist. Most were conducted with engineers in R&D labs [15] rather than those in diverse workplaces.

Method

During the spring and summer, 2004, we conducted structured interviews with 110 volunteer practicing engineers solicited from the ranks of the Missouri Society of Professional Engineers. Demographic information about the engineers and their workplace contexts are presented in Table 1. The interview focused on a single job or project that had been completed by the engineer during their career. We made no attempt to influence the nature of the story that was recalled. We asked questions regarding the engineers' academic preparation, the organizational context in which they worked, the nature of the project, how they analyzed and represented the problem, how they generated solutions, and how successfully the job was completed. A total of 98 interviews were transcribed (technical difficulties affected the remainder).

<u>Engineering education</u>: civil (39), electrical (18), chemical (10), mechanical (13), structural (5), industrial, nuclear (1), other (16)
<u>Engineering education level</u>: bachelors (70), masters (30), doctoral (0)
<u>Professional engineering experience</u> (15.3 years)
<u>Business size</u>: 1-20 (21), 21-100 (29), 101-500 (17), 501-1000 (33)
<u>Department size</u>: 1-10 (40), 11-50 (22), 51-75 (7), 76-100 31)
<u>Problem size</u>: large (45), midsize (43), small (12)
<u>Department type</u>: chemical (0), civil (14), electrical (20), industrial (0), mechanical (7), product development (11), safety (7), quality control (11, executive level (20)

Table 1. Demographic information about interviewees (values in parentheses are percentages.)

We treated the interviews as multiple case studies, on which we employed a modified analytic induction process, "a qualitative research method that uses a systematic set of procedures to develop an inductively derived grounded theory about a phenomenon" [16]. Analytic induction provided an ideal methodology for identifying themes and categories within engineering stories. By utilizing a multi-case design, several experiences were compared and contrasted. In the analytical induction approach, data built the basis for further descriptions and interpretations, but as the term 'induction' indicates, the methodology did not employ an atheoretical empiricism, but was a form of induction making use of categories that was informed by CBR.

Collecting and coding the interview transcripts began by examining the interview protocols for salient categories of information that were supported by the text, identifying categories of information. We used the qualitative research tool, Qualrus, to code themes and categories and associate interview text with the categories. The categories or themes emerged from the data. The coding of the categories was the means for establishing similarities and differences among the cases and for redefining the categories/themes during the process. After the initial process of open coding, axial coding reduced the first set of codes by merging similar codes and reassigning codes to particular text elements.

Results

The following themes emerged during qualitative analysis.

Theme 1. Most constraints are non-engineering. Most engineering education programs treat problems as engineering-only problems. However, when the engineers talked about constraints, the constraints were most often unrelated to engineering. When constraints come from politicians or citizens, the constraints are usually political or social in nature. When the clients are other companies, the constraints are determined by cost, functionality, and the requirements that new solutions have to work together with elements already in place. Workplace problems are made more complex and ill-structured because of political constraints, such as regulations or acceptability to citizens; environmental constraints, such as requirements to meet environmental regulations or obtain permits; economic constraints, most often dealing with the budget; cultural constraints, such as the corporate culture or local context. Examples of these constraints include:

> We are solving a whole series of things in the fact that an architect or owner wants to build a building a certain way, and he has certain needs and desires, but yet we have all these safety codes that need to be met.
>
> …the state … building and Fire Department that had their whole set of requirements, and we had to make sure that those requirements also didn't pose problems. So we had a whole series of requirements, one playing off against the other that we had to balance out.
>
> And there were several environmental issues up there, concerns from US Fish and Wildlife that we were going to hurt the fish.
>
> And we had to get some extra power to run our treatment system so we had to work with the local utility company. Had to work with some rental companies for equipment rental. We had to work with the EPA and the Department of Natural Resources and briefly with the local emergency planning committee.

Constraints often result from biases, such as personal preferences on the part of the client. We also note that engineering problems are frequently subject to multiple non-engineering constraints.

Theme 2. Success is rarely measured by engineering standards. Engineering educators often assume that engineering problems should be solved using only engineering criteria. The ultimate engineering criterion is failure [17]. Virtually every calculation that an engineer makes is a failure calculation. However, the success of engineering projects is rarely measured by engineering standards alone. When asked what made their problem solutions successful, engineers claimed that staying under budget and satisfying the client were paramount. Rarely were engineering standards used to determine success. Even when asked about different solutions and how they interplay, there was little mention of more sound engineering solutions. The following excerpts describe how these criteria applied to engineering problems.

> So we are pretty savvy as to understanding what the code is trying to say. You have some people in these code-making bodies that you can consult to make formal interpretations and written interpretations.

> So we had to make sure the bank would give us a line of credit, and we had to talk to our client to see if they would pay us some up front money to start building these systems. Funding was a big concern and we have to make sure we have enough.

> Legal constraints—as long as we are complying to the law and we want to make sure the client is not asking us to do something illegal. We also want to make sure that we have a contract where every party is happy. if that is possible. Make sure we get paid, and they understand what we are going to do, and we understand what they are expectations are.

Although solutions must meet implied or explicit engineering standards, according to our data, those are rarely the standards that are used to describe the success of a project. The ultimate solution criteria seemed to be whether the client was satisfied and whether the project was profitable.

Theme 3. Workplace problems (problems in the wild) are ill structured. Every problem solved in everyday engineering contexts that was reported to us was ill structured. Initially, some problems appeared fairly well structured, however, as constraints became apparent, the problems became more ill structured. While the engineering activities often formed the core of the problem solution process, the entailments from those activities (working with other people, dealing with environmental constraints, and managing the project) made the problems ill structured, as evidenced in the following excerpts.

> If you've got a major water line, and it's out of the right of way, you're going to have to work with that utility to move that line and then figure out who has to pay for that move. So utilities are always a pain in the ass to work with.

> Well, trying to build it in such a flat area with so little drainage, the grade was almost flat, less than a half percent, or less than a percent in some places. And it's very difficult to pave parking lots and expect them to drain when it's that flat.

> So part of the problem was to be able to come up with a system that would be able to actually track the rolls accurately.

Often, problems in projects do not occur until after the project has ostensibly been completed. This raises the issue of when a problem is solved. What obligations do engineers have to clients after they are paid for a project? A civil engineer provided the following example.

> The problem just showed up10 or 12 years after construction, and we never did really find out why it showed up 10 or 12 years after construction, but we did get the mix optimized and everything for that, and hopefully we won't have that problem in the future, but we're not sure exactly why, what was causing some cracking problems later on in life.

Theme 4. Ill-structured problems contain smaller well-structured problems. With design problems, one of the most common types of problems solved by engineers, the bulk of the time is spent by junior staff drawing the ideas and "making it work". Within large projects, numerous well-structured problems are solved, such as "what is the load strength for material x" and how big is the radius of machinery y. While engineering students solve well-structured problems in university classrooms, those problems aggregate in unpredictable ways in everyday contexts. Two engineers provide relevant examples of this theme.

> We had to decide how big a lagoon to hold the dirt and the possible rain for the possible amount of time we were treating this soil. And we had to decide how best to treat the soil. We had to make calculations how long that would take and put back into the ground. As we are doing all of this to decide where we would sample the soil, we had to figure out what we were going to find in the hole, how we would treat it so that we would know about the size and what to put in our water treatment system and how we were going to power it. So those were a few of the decision we needed to make.

> With all the data that we collected out in the field on the performance of them in the past years, we looked at which had the fewest cracks, which had come loose the most, which had the fewest repairs, and which were more impermeable to chlorite, to salt that gets down in them and corrodes the rebar, and that was basically it. There's a little bit of how workable the mixes are when you're putting them down, but that was kind of eliminated by the 4 that we picked. It was analyzing the data and then also trying to confirm that with some other state DOTs that had used the same thing.

Theme 5. Problems are driven by multiple, often-conflicting goals. The problem solving process has an overall goal and sub-goals. A big portion of the problem solving process is to reconcile the sub-goals so they align to support a solution for the main goals. These goals can be conflicting, and engineers must decide which goals have higher priority.

> We are trying to understand everything that the owner is trying to do and create for him on paper a design that is creative yet meets all the applicable codes and provides the level of protection that the owner needs not only today but also in the future. So it provides him flexibility.

> But we have construction types that are fire resistant, automatic sprinkler systems automatic smoke detection systems, a high level of security, occupant notification systems that immediately begin to evacuate certain areas automatically. So there is a whole series of a lot of different safe guards -automatic and mechanical safeguards.
>
> Our job was to actually do the work. To operate the machines that cleans it, to build the lagoon and volatize it, and to build water treatment systems to treat the water.

Even the bottom line contains multiple goals, as expressed by a construction engineer.

> Our goal is to always work safely and make money. Safely and on time and make our client happy and to get additional work from our client.

Theme 6. Most problems require collaboration with other engineers and non-engineers. As Theme 4 showed, most workplace engineering problems are actually aggregates of smaller problems. Those smaller problems are usually distributed among a variety of staff, such as draftspersons, surveyors, other engineers, and administrators. Because of the size of the problems described by the engineers in this study, the amount and diversity of partners required to complete the projects was high. Engineers rarely solve problems by themselves. In order to solve complex problems, team members must interact constructively, as evidenced by the following interview excerpts.

> I oversee several sections, I oversee our design section, our planning section, our right away section and we have a general services section, I do that too.
>
> At the owner's facility, he had probably six or eight engineers involved. We had three or four operations people. And then we had two or three maintenance people involved. And then plus we had contractors. We had mechanical contractors doing the ductwork, installation, we had electrical contractor doing the wiring. And then we had a sub contractor at Honeywell, who provided modifications to their control system.
>
> I mentioned we had cooperation with water and utilities. They're responsible for all the sewer lines once they're constructed. We also had to work closely with purchasing and the administration department in getting the bidding set up and the advertising properly done. And in the administration department, our city administrators are the ones who help guide us through the political stuff.

Sometimes, collaborations are successful because the roles and relationships are well defined, and (like any good system), they share a common goal.

> We all pretty much know our roles but know that in our specialization those people touch on certain things affect the fire protection engineering and life safety.
>
> We are all working together for a common goal, which is to make sure that we have an economically viable building and a safe building-one that is going to function the proper way. We all sit down at the conference table together and we come up with a

> plan and then we work very closely with the engineering disciplines so we have all the details ironed out.

In considering the implications of this theme, we must better understand the intersections between separate teams of engineers. How do they interact? How much knowledge about the other persons work is necessary to get one engineer's work done? Follow-up studies should more closely examine the nature of these interactions.

Theme 7: Engineering problems often encounter unanticipated problems. Most everyday problems are dynamic, that is, the conditions change over time. Most all of the problems the engineers talked about were large scale or small-scale projects, in which a set of problems (some of which were unanticipated) occurred. What is interesting is that the unanticipated problems that arose were a combination of engineering and non-engineering problems, as described by an electrical engineer.

> Also at different times we don't live in a perfect world and when buildings get put together at times people can make mistakes. Sometimes they can't be rectified and need to be ripped out and other times it would be disastrous to do that, so we develop equivalency concepts for that. The other unanticipated thing is you can get in a project is that the owner can change his mind and all of a sudden the whole dynamics of the project changes.

Often, unanticipated problems can aggregate, making the projects even more complex to solve.

> We had some unusual rain and we planned on operating the water treatment about 8 hours a day while we were down there working occasionally because of the rain we had to send men down there over night or over the weekend to operate the water treatment system. As we dug they didn't tell us what used to be there we found pipes with asbestos on it, we found some unexploded ordinance, this used to be an Army base where they used to make rockets so the client didn't provide us with good information as to what we might find.
>
> The contract wasn't specific enough. We were working for another consultant. The chain of command was the client's consultant hired our consultant who hired us. We could only talk to our consultant and some of these things have to be made right then. And the chain of command delayed things a lot. If we had it do over we would have made it easier to get an answer more quickly. We encountered some chemicals in our water treatment that I did not expect. We were able to adjust but it took a little while. If we had it to do over we would have done our own sampling to confirm what was in the water. We did not get a lot of things in writing and later we had trouble collecting. Maybe writing up change orders would have been good.

This latter problem emphasized the need for clear communications among engineers, a theme that is reflected in recommendations from the engineers (next theme). One engineer summarized this theme of unanticipated problems quite well:

> For a project that size, it's my experience that you're always going to have things come up that you don't anticipate.

8. Engineers rarely recommend more engineering in engineering curricula. Most engineers felt well prepared for core engineering jobs, however, there is a general acceptance among most engineers that graduates will "really" learn how to be an engineer during the first year or two on the job. Rarely did practicing engineers recommend more engineering in engineering curricula. Rather, most of the engineers emphasized more instruction on client interaction, collaboration, making oral presentations, and writing, as well as the ability to deal with ambiguity and complexity. As two engineers opined:

> …it is kind of a sore spot with me that educational institutions teach when you do your work there is a right answer and a wrong answer. And in the real world it is never that way, there are many ways to do things and it is not a matter of getting a right answer it's a matter working to the best solution for your particular situation.

> …. in school you have to do your own work and your expected not to cheat and in the business world you solve everything on a cooperative basis." Therefore, engineers must learn to communicate: "Make sure engineering-wise, in addition to their raw engineering they have good written and communication skills and make sure that they don't get tunnel vision.

Implications

Most engineering education programs engage their students in problem solving. However, the most common kind of problem that is solved is the story problem, found at the back of mechanics, statics and dynamics textbook chapters. These are well-structured problems that have correct solutions and convergent solution paths. Educators believe that solving these well-structured problems prepares learners to be able to solve ill-structured problems. Recent research has shown that learning to solve well-structured problems does not transfer to ill-structured problems; solving well-structured problems calls on different processes from those that are used for ill-structured ones [18, 19, 20].

In order to expose students to the ill-structured nature of everyday problem solving, many programs provide capstone experiences or PBL experiences. Capstone courses are valuable experiences, however, they are probably inadequate to prepare students to accommodate the complexities and ambiguities of workplace problem solving. PBL experiences rarely involve the complexities and ambiguities of workplace problem solving. Most PBL programs focus only on the engineering aspects of engineering problems. The problems that engage students must require that learners

- reconcile multiple, conflicting constraints and criteria
- Manage multiple sub-problems
- Communicate and negotiate with other engineers and non-engineers
- Adapt to changing project conditions and unanticipated problems.

These skills cannot be learned in the context of well-structured, textbook problems or constrained PBL programs. If engineering educators are to insure that all engineering students gain these skills, we need models for designing these experiences and the environments that support them. That goal is one of the major foci of the Center for the Study of STEM Problem Solving that is being proposed to NSF.

Note

1. This research was funded by the National Science Foundation (NSF–0350305) as part of the activities of the Center for the Study of Problem Solving.

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