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Characterization of Techniques used in Industry: The Practice of Complex Problem Solving in Engineering

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Abstract

There is a gap between academia and industry in terms of how students are taught to solve complex problems and how professionals solve complex problems in industry. This paper will begin to explore the tools and techniques professional engineers use in their work. Face-to-face interviews were conducted with professionals employed in engineering roles. The interview protocol asked the engineers to identify tools and techniques they use for complex problem solving. A preliminary analysis of five participants' interviews revealed four tool or techniques used in complex problem solving in industrial settings: lean and/or Six Sigma, risk management, data management, and communication across teams. Ultimately, we envision the results of this work will lead to recommendations for curricular interventions and reform in STEM education to bridge the academic-industry divide.

I. Introduction

There is a gap between academia and industry in terms of how students are taught to solve complex problems and how complex problems are solved in industrial settings. This gap is caused by pressures in the world market that call for different critical skills. These pressures then result in changes in industry's expectations of their workforce. As such there is a need to identify and characterize the tools and techniques that are used by engineers in industry to solve complex problems, particularly in research and development and design. Similarly there is a need to identify and characterize the tools and techniques for solving complex problem taught in science, technology, engineering and mathematics (STEM) programs.

In this study, we are interviewing practicing engineers about the tools and techniques they use in their daily roles in solving complex problems and the extent to which they were taught about these tools and techniques during their college education. Our working definition of complex problem solving is "[When] solving occurs to overcome barriers desired between a given state and a goal state, by means of behavioral and/or cognitive, multistep activities" (Jonassen, 2017, p. 28). This paper will describe the complex problems faced by engineers and the tools that are used to solve these complex problems. The common problems will be determined by comparing and contrasting the purpose of the tools and techniques and how the tools and techniques were utilized that were identified in the conducted interviews. Other information was gathered, such as what benefited the interviewee the most in university will be analyzed as well in order to have a deeper understanding of the complex problems they solve.

II. Background

Complex problem solving is the main occupation of any professional engineer. Learning how to solve complex problems requires learning tools and techniques that can be used to solve those problems. Jonassen (1997) discussed how to solve defined problems versus ill-defined problems. For defined problems, "using analogical problems requires that learners recognize the similarity between the previous and current problems and that the learner can recall the solution method used in the previous problem (Reed,1992).” (Jonassen, 1997, p. 71). This is beneficial to a student in the beginning as solving fundamental problems on a foreign topic needs practice. Eventually, if the student pursues further study and enters the profession, the student will encounter ill-defined problems (complex problems). Jonassen (1997) found that “ill-structured problems [to] require that learners assemble a large amount of relevant, problem-related information from memory (Voss & Post, 1989). Learners cannot retrieve the appropriate rules from the chapter(s) being studied. Ill-structured problems engage a broader range of conceptual knowledge about the problem domain” (Jonassen, 1997, p. 78). This difference in defined and ill-defined problems is one of the major key points of the gap between academia and industry. By collecting tools and techniques that professional engineers use in their daily lives to solve complex problems, a happy medium can be found that incorporates learning to solve both types of problems to better prepare the student.

The gap between industry and classroom has been mentioned in many works, but the topic is a difficult one to discuss as there is a lack of empirical data that can be used to support research. Researchers like Stevens addresses this gap between engineering faculty and engineering professionals. He notes that “the work of engineering faculty involves teaching and research, as well as many activities that maintain the going concerns of their workplaces, which are universities. Engineering research is of course a form of engineering work, but its accountabilities are clearly different from the work practices of engineering professionals outside of academia who are involved in realizing engineering projects” (Stevens & Johri & O’Connor, 2013, 132). In this paper, the gap will be focused the on how students are taught to solve complex problems and how professionals solve complex problems in industry. This gap is explored by interviewing engineering professionals on the tools and techniques they use in their daily work to solve complex problems.

The academia-industry gap is caused by a disconnect between industry expectations and the university standards. In the *Hart Research Associates* study (2015), the researchers found two key points that define the reason for the gap.

1. “Employers are more likely than college students to see room for colleges and universities to improve in ensuring graduates possess the full set of skills and knowledges needed for success.” (p. 9)
2. “Many employers feel that colleges graduates are falling short in their preparedness in several areas, including the ones employees deem most important for workplace success. College students are notably more optimistic about their level of preparedness across learning outcomes, however.” (9. 11)

The top four skills that employers look for that cut across majors are oral communication, effective teamwork, written communication and ethical judgment and decision making. This specifies where the gaps are occurring between industry and academia. Employers want employees that are more experienced in working teams effectively as that is how industry works, very few people ever work alone.

This research paper has a preliminary analysis of five participants' interviews revealed four tool or techniques used in complex problem solving in industrial settings: lean and/or Six Sigma, risk management, data management, and communication across teams. Ultimately, we envision the results of this work will lead to recommendations for curricular interventions and reform in STEM education to bridge the academic-industry divide.

III. Method

III.A. Setting & Participants

The subjects of this study were professionals working in in industry in research and development, management, and design. This participant group represented individuals who solve complex problems and can best provide information about the tools and techniques used in industrial settings for solving complex problems. Initially, subjects were identified from the personal networks of the authors. Additional subjects were identified via the subjects themselves who were asked if they know of and are willing to share the name and contact information of a professional working in research and development and design in industry that they believe would be interested in this study. Each potential subject received an invitation to participate in the study. The interviews of five participants are used in this preliminary analysis (Table 1).

Table 1. Participant key demographics.

Interviewee (Pseudonym)	Degree	Career/Position
Daniel	Technology	Design Engineer
Jack	Aerospace Engineering	Research and Development
Lola	Chemical Engineering	Product Researcher
Matt	Mechanical Engineering	Senior Materials Engineer
Ronald	Chemical Engineering	Senior material Product Developer

Interviews

The participants were interviewed about the tools and techniques they use to solve complex problems in their work. Participants were sent an email invitation to participate. Participants participated in a face-to-face, online (e.g. Skype, Google Talk), or phone interview that was audio recorded. The interview was designed to be 40 to 60 minutes or shorter in duration. Audio recordings were transcribed with pseudonyms for the individual and company. As needed, a member check was done to improve the accuracy, credibility, validity, and transferability of the study. In other words, participants were contacted to verify facts in their interview and check the characterization of the tools and techniques they reported using in their interview. In particular, descriptions of company proprietary tools and techniques were checked to ensure non-disclosure of sensitive company information.

The interview protocol is provided in the Appendix. The interview protocol's purpose was to ask questions in a way that would identify the formal processes/tools/techniques/models that professional engineers use and then how, when and why they use these formal processes/tools/techniques/models. This allowed for an in depth understanding of the formal processes/tools/techniques/models given to the interviewer and allow for comparison.

Data Analysis

The interview data are being analyzed using open coding and content analysis. For this work-in-progress, initial codes were identified via a first read (Creswell, 2008; Patton, 2002). These initial codes are the tools and techniques used in complex problem solving in industry as discussed by the participants. For each of these initial codes, the code is described and supported with quotes from the participants.

IV. Results & Discussion

Four main themes were coded from the texts of the interviews. These four themes are: Lean and/or Six Sigma, Risk Management, Data Analysis, and Communication Across Teams. Each theme is described below.

IV.A. Lean and/or Six Sigma

All five interviewees at one point at least mentioned that Lean and/or Six Sigma problem solving has been part of their technical problem solving process. Lean or leanness is defined by J. B. Naylor as ”developing a value stream to eliminate all waste, including time, and to ensure a level schedule” (Naylor & Naim & Berry, 1999, p. 108). According to Tjahjono and Ball, Six Sigma can be thought of in one of four ways: (1) “a set of statistical tools”, (2) “an operational philosophy of management”, (3) a “business culture”, and (4) “an analysis methodology” (p. 6-7). The interviewees made reference to the fourth way of thinking about Six Sigma. “Kumar et al. (2007) argued that Six Sigma is an extension to quality improvement initiatives such as the Total Quality Management (TQM) because of the similarities between the Six Sigma method of Design, Measure, Analyse, Improve, Control (DMAIC) and the Deming's PDCA (Plan, Do, Check, and Act).”(Tjahjono et al., 2010, p. 7).

Daniel, Ronald and Matt, three out of the five interviewees used Six Sigma methodology in daily problem solving. Referring to the four definitions above, the interviewees focused on the fourth definition of analysis methodology. Lola used to use the fourth methodology in university, but is now focused on the statistical definition of six sigma.

Daniel, discussed the use of Six Sigma as a very technical tool. Daniel did not major in engineering, however his occupation requires the thought processes of one and he found that the DMAIC helpful for engineering problem solving.

> "When you have manufacturing issues, that's a problem that has to be solved, something that I had learned both in a class at [university] and any place that has a manufacturing component to what they do. Often-time it is engineering or technicians that are handling the manufacturing area and so they use what is called six sigma methodology. It was motorola … and they started this program and it was a manufacturing problem solving methodology and you had to learn the acronym DMAIC for define, measure, analyze, improve which means solve the problem and c for control - don't just walk away from the problem and assume that it will work forever - then control the situation."

Ronald uses Six Sigma under the name of LEAN which entails very similiar problem solving steps to DMAIC. For LEAN, the first step is to identify the problem; the second step is to identify countermeasures to the problem. The third step is to test out these countermeasure and then as the fourth step is to verify that these countermeasures work. Ronald explained how the LEAN problem solving process can be used in real life situations to make the technique better understood.

> "If your car battery is dead, [you might think] I need a new battery. Well how do you know that it's your battery? It could be your battery, it could be the alternator. Maybe you left your lights on. So let's go test those three things. Well, your light switch is on, so you must have left your lights on - well there's one. You charge the battery to test the hypothesis and the car will start but then the battery is dead the next day. Your battery appears to be good, so let's check the alternator is charging the battery. You find your alternator is bad and not charging the battery when running. So that's how you figure that's your problem. Most people go straight to 'Oh I know what the problem is and I am going to solve it.' If you go through with that example and bought a new battery then you're out of a hundred dollars and you still don't have an alternator that works."

LEAN was introduced to Ronald at the company he works at, so he was never formally introduced to LEAN during his education. He tests and developed methods that solves problems at the company that he works for. He notes that at his time learning chemical engineering at university, there was a large focus on learning methodology, but he wished there was more emphasis on decision and analysis and locating root cause.

Matt did not mention LEAN, but instead discussed Six Sigma and his process that he based off of the technique. Step one is to see the problem and step two is to then to explore the problem with software or computer models. Step two involves collecting empirical data that can become very complicated, so then Matt uses proprietary software to organize the data in a way that is useful to him. Matt described these software by discussing how he utilizes them.

> "I have computer models that are available to me that I have developed [or] have had other people develope for me. And I will use those computer models to simulate a particular issue…Most of the computer models that we have are excel based with VBA. VBA is an add on package for excel, so basically VBA is a convenient way to program excel to do

things for you... VBA is a subset for excel, so let's say you have a bunch of data in columns or rows, but you want to condense that and analyze this say statics of it. In industry it is common for us to collect thousands and thousands and thousands of parameters and were drowning in data. Data is no good unless you can analyze it and present it in a format that makes a pressing business case."

Lola had a similar experience as Ronald. At university studying to be a chemical engineer, she learned Six Sigma in terms of DMAIC and then applied the tool for the first two years of her career. Now she is much more focused on the management of how, what and why technical problems are solved, so her personal use of the tool for the fourth definition is low. However she does statistical work now and the first definition is more applicable to Lola's use of the methodology.

IV.B. Risk Management

Understanding risk is an enormous component of problem solving in industry. Risk is defined in this paper to be the financial risk an industry faces when taking on a project. These risks typically lie in the loss of millions of dollars or not meeting the goals of the quarter. Lola, who is an engineer working in management, notices that in school she had not heavily considered the aspect of risk when taking on certain projects in academic training. When entering the industrial setting, they had to learn how to identify, quantify, and communicate risk. Risk is carried throughout an entire project by the means of unknowns. Unknowns largely have to do with the amount of time certain parts of a project would take, how much money would be needed, and if the market will react positively to the results of the project. Many times the project will begin with determining what they know, what they don't know, and the potential risks that can result from not knowing.

> "The commercial and marketing team, they are looking at the long term vision and what they want the shelves to look like in ten years...They are responsible for making sure we make our financial goals at the end of the year… So they will fill in and say "We need to have this project and this project done this year." because they are predicting that they are going to bring in this much… When we are inventing something new, part of the risk is we might fail that clinical. And if we fail that clinical then they are not going to meet thier money for the year. So what we try to do is take everything and say "What are all the unknowns and which one of those have the potential to kill a project."... It's better to fail early than the fail later, because then it gives them time on the marketing side to react and fill in the gap with a different project."

Risks that are more likely to terminate a project are addressed immediately to better understand the project's weak points. Experience in finding risks and seeing the consequences and learning from those consequences is what makes an engineer useful in industry because she knows what makes a project potentially successful or a failure from the beginning.

This is valuable because in industry there is a greater focus on the long term rather than the short term goal. The marketing division is often responsible for meeting the financial goals for the year, so they often set timelines for certain projects to achieve those goals. An example from Lola about how this process works is that marketing will assess and choose which projects will make up the financial goal for the year. The risk associated with this is that if a new product is being developed and the marketing division wants the product done by a certain time, clinical trials may not be approved or technical work can take longer. Getting a feel for this type of risk during one's engineering education is important because this is what can happen in industry and engineers need be prepared for this setting. Lola has also been working to help find a balance between using systems and critical thinking due to over systemization.

> "We have tried to systemize so much of our work that we have taken out that whole human factor. Sometimes I think that, I have communicated this, if we systemize everything and a lot of that is to reduce risk. It's put there because something thing happened there and we put a process in place. But as we become more that way we end up loosing basic common sense. We don't enable people to just use their brains and enable themselves. We have moved away from that."

Lola and others in management have shifted to making the projects more personal, so the whole team can understand the risks better. Lola explained that asking questions such as "If this was your business what would you do?" and "What keeps you awake at night?" helps to force the team to make decisions based on technical data and critical thinking. This type of thinking leads to early risk detection which is highly rewarded. At Lola's company, the marketing department determines the quota for the year. Marketing looks over the projects that Lola's team is completing and picks which ones need to be completed that year for the quota. Being able to detect risks allows for marketing to react better to when projects fail and replace failed projects with new projects before the consequences get out of hand.

Matt was not as descriptive on risk analysis as Lola, but he had a very similar way of determining which problems were actually worth solving in terms of what financial risks they solved.

> "If we see something that's unique or a mystery and if its truely a million dollar or more problem and it looks like it is going to be a long term problem... then we will make an effort to develop a computer model to understand the issue."

Problems that are less than a million dollars do not have as large of an impact on company profits and those kinds of problems tend to take longer than thousand dollar projects. Determining which problems to take on is a risk evaluation as certain problems have a greater impact financially than others.

IV.C. Collecting and Using Data

Many engineers in industry are faced with the large task of finding, understanding, and analyzing data. Jack's greatest task while solving a problem is finding data, attaining the correct understanding of the data, sorting and organizing the data, and using the data accurately. The clients that he works with need to have strong quantitative data to support the solutions that he provides for their problems.

> “My work with... former executives… They have had a lot of experience in ship building, project management, operations, or other things. The experience means there is a lot of insight to the processes and the data... I never take what anyone tells me without finding numbers based to back up what I have been told. So if I am told, this is the way it is, I say I can’t use that statement because the statements are just being based off gut instinct. Show me the data that says that's the way it is otherwise I can’t use the statement. It keeps us from making bad decisions based on the data. So, I will do a data exploration and then I will show it to the team and we will talk about it…. And then we start to model and it could be that it is a preexisting model that we have modified if it might work, but more often than not it's developing a new tool or model for this specific purpose.”

A way this is approached is first with a kick off meeting to have an understanding of what questions the data is supposed be solving. Next is to collect data which allows Jack to have a broader understanding of what data he is already working with and what new data he might need to collect.

> “So after the initial kickoff meeting, my first job typically is to collect data. I will collect the data to see what I can do with it. Now I see that it is inverted from how we are trained as engineers, where we define the problem first and then we collect data to answer the question. I’ve learned here, it was a very hard lesson because I was trying to define the problem and then find the data. Often times data doesn’t exist again because nobody has really understood the question they are asking. There's not data sitting somewhere that can readily answer my question. A big part of my work is actually finding data and figuring out what it means.”

After this in-depth preliminary search, another meeting is held with a team and the client to make sure the question is being addressed and is heading in the right direction based on the data collected. This is also where the data must be confirmed for what it appears to be. If the data cannot be found, often times the client has heard of data or knows of someone who would have access to such data and connects them with that person. If no connection can be found then the team must collect it themselves. A final step before releasing findings is a team meeting to ensure that the same conclusions has been drawn from the data found and collected.

Similar steps were used by Matt when handling problems that occur on the assembly line with no easily discernible pattern. First the problem is detected and assessed for value. Million dollar projects are typically the only one Matt handles as those have enormous impacts. When handling problems with no easily discernible pattern, he uses data acquisition services to get an in-depth look at the problem. They set up sensors that collect high quality data for three days and then gain three days worth of cycles of empirical data. Then the data is assessed for what is happening when the problems is occurring to see what the cause of the issue is. After data is collected and analyzed, it must be presented to management, so the issue can be resolved. A common problem Matt sees is that engineers attempt to present complicated data to people on management who have no technical background. The data must be condensed, summarized, and presented in a way that makes the conclusion derived from the data clear to anyone.

IV.D. Communication Across Teams

In industry, projects are often tackled by teams that are then connected to smaller subsets of teams. Communicating in such environments is especially difficult as group members can number into the hundreds. For this reason, an industry might purchase software to facilitate product lifecycle management. For instance, SmarTeam can be used to store all all digital documents (CAD, reports, spreadsheets, data) and control workflow to make communication within teams simpler Dassault Systemes, (2017). Daniel stated that early in his career there were issues with workflow that impacted the way communication on projects was done.

> “The computer program handles the flow of information and the iterations of documents and saves all the individual iterations of documents so you're never saving over a document, so you always have version 1,2 and so on. Workflow is helping send the information to the right person whether it's the acoustics engineer or the design engineers or the review team or the people that will do the cost information and then ultimately to the person that will send all the completed information to the customer."

Communicating across teams with different goals also occurs in industry. Technical and management track engineers tend to find partners in the opposite track at the industry of Lola. This allows for management people to have better access to the data collected by technical people and determine a purpose for the data. This tends to be a useful way of organizing communication between large teams as it divides the number of people by two due to how closely they work together.

> “I have people that I don’t necessarily manage, I call them my t-partner, technical partner. They are at the same level as me, so it's not like I manage them, we don't really look at it like that. I am just your partner that takes care of all the management stuff.”

Lola also noted that, because of the sheer size of teams, it is important from the beginning to make sure no one is doing the same thing. In the beginning of projects, she has the people she partners with send her a list that defines their potential work for the project and if any of them match, she suggests they work together or focus on something else.

V. Discussion & Conclusion

The five participants in this preliminary study discussed four tools and techniques for solving complex problems. These are summarized in Table 2.

Table 2. Summary of codes

Codes	Key Points	Similarities	Differences
Lean and/or Six Sigma	● process improvement methods ● improvement initiative (DMAIC) ● four interviewees mentioned Six Sigma, one mentioned Lean	● Used in technical roles ● All used at some point in career regardless of university major	● Used different variations of Six Sigma with specific steps of DMAIC
Risk Management	● financial risk an industry faces in taking on projects ● only mentioned by Lola (non technical)	● the initial steps of determining if a certain project is worth pursuing ● Matt did not mention risk, but had similar assessments	● Risk was not discussed by majority of interviewees
Collection and Use of Data	● the large task of finding, understanding and analyzing data	● two focused on this concept ● most work comes from data analysis	● different reasons for collecting data
Communication Across Teams	● projects are targeted in large groups made of subsets numbering in the 100s ● communication can be difficult	● Companies that have a main technique tend to communicate better	● Jack works mostly alone, but confers with others for confirmation

There is a need to identify and characterize the tools and techniques that are used by professionals in industry to solve complex problems, particularly in research and development or design. This characterization of the tools and techniques used in industry could be used to guide the design of more authentic engineering instruction in academia. The resulting instruction would better prepare students to solve real world complex problems and allow them to have a greater understanding of the practice of engineering before entering the industrial setting. We anticipate that the characteristic features of the tools and techniques used by professional engineers to solve complex problems are only loosely related to those taught in undergraduate programs and even more distant from what is taught in K-12.

Jonassen, Strobel, and Lee (2006) identified various types of problems that engineering students should be solving in the classroom setting. Most relevant to the codes identified in this paper are that students should have experience with:

1. Analyzing and selecting from a variety of solutions to various problems and to justify their selected solutions
2. Identifying and reconciling methods for achieving non-engineering criteria for solving problems
3. Communicating and collaborating with a variety of professional and paraprofessional team members on all aspects of the problem-solving process
4. Anticipating and reconciling intervening problems and perturbations to the problem-solving process
5. Adapting to changing project conditions and unanticipated problems
6. Using multiple tools and formalisms (visual, verbal, quantitative) to represent problems
7. Engaging directly or vicariously the complexities of workplace problems as often as possible - "they should have some classes or something where you could have got to go out in the field a little bit and see some of this stuff" (Jonassen, Strobel, & Lee, 2006, p 147-148).

Each of these problems can be linked to one of the codes determined in this work-in-progress study. Problem type 1 is a data collection and analysis problem. Problem types 2, 6, 7 aligns to Lean Six Sigma. Problem type 4 and 5 relate to risk management. Problem type 3 relates communication across teams. Of particular note here is the direct correlation with problem type 7 and comments made by interviewees Matt and Ronald as both stated that in order to initiate complex problem solving, they had to go see the problem in real life.

Crismond and Adams (2012) discussed nine techniques that can be used by STEM teachers in K-16 to better educate their students about the field of engineering. Matrix pattern A (Problem Solving and Problem Framing), discusses the problems that young designers face as they attempt to solve a problem, "Observing the initial moments after beginning designers are given a design problem, especially younger children, will probably reveal some team members quickly grabbing some materials and attempting to solve the problem with little talk and forethought, or immediately devising plans to solve the problem… They may generate solutions prematurely because they assume that all that they needed to know has been provided for them in the problem statement." (Crismond & Adams, 2012, p. 747). This one matrix addresses all four of the themes discussed above, but instead of from an professional engineer's perspective, they are deriving the matrices from observations of how younger designers handle problems versus experienced designers The lack of thought about problem solving steps is related to the Lean Six Sigma code. Solving problems with no forethought connects to the theme of risk management. The lack of communication addresses the theme of communication problems between engineers. The assumption that no data collection is needed hits upon the theme of collecting and using data.

The research of Jonassen, Strobel, and Lee (2006) and Crismond and Adams (2012) have focused on the necessary tools and techniques that need to be taught in the academic setting. In combination with the findings from practicing engineers (as in this paper), the gap between industry and the academic setting can be reduced. Ultimately, we envision the results of this work, in combination with that of others, leading to recommendations for curricular interventions and reform in STEM education to bridge the gap.

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Appendix A. Interview Protocol

The overall purpose of this research is understand the difference between the tools and techniques for solving complex problem used in industry and those taught in science, technology, engineering and mathematics (STEM) programs. The results of this work will lead to recommendations for curricular interventions and reform in STEM education to bridge the gap between school learning and practice.

1. What is your role or job function at this company?

2. What kind of problems do you solve in your role at this company?

3. In your work, what kinds of formal processes/tools/techniques/models do you use to solve complex problems?

   Follow-up Prompt: For instance, when launching into a new design project, what tools or techniques do you use to scope the problem?

4. I am going to ask you a series of questions about each of these: [Repeat for each tool or technique]

   a. Is this a proprietary processes/tools/techniques/model?

      [If the response is yes] As stated in your informed consent, the characterization of this processes/tools/techniques/model will be generalized during our data analysis and reporting to ensure non-disclosure of sensitive company information. We will member check this generalized characterization with you during our data analysis and before dissemination of research results.

   b. What kind of problems is this processes/tool/technique/model used for?

      Follow-up prompt: When you are working on a project, what does this processes/tool/technique/mode help you do?

   c. When did you begin to use this processes/tool/technique/model?

   d. Why did you begin using this processes/tool/technique/model?

      Follow-up prompt: What caused you to need this tool or technique?

   e. What in your education prepared you to use this process/tool/technique/model?

   f. How often is this processes/tool/technique/model used by you?

   g. Can you describe an example of when you used this process/tool/technique/model?

   h. Are there any positives/benefits to using this process/tool/technique/model?

   i. Are there any negatives/limitations to using this process/tool/technique/model?

5. Are there any other processes/tools/techniques/models that you use that we have not already discussed?

6. How do you learn about new processes/tools/techniques/models?

7. How do new processes/tools/techniques/models get incorporated into your work?