AC 2008-1546: ANALYSIS OF VERBAL DATA FROM AUTOMATED SYSTEM DESIGN PROBLEM-SOLVING

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Analysis of Verbal Data from Automated System Design Problem-Solving

Automated systems play an essential role in manufacturing, from assembling complex electronic devices to mixing pharmaceuticals. Engineers must constantly design, maintain, reconfigure, and upgrade these systems to accommodate shifts in product design or manufacturing priorities. Their ability to rapidly complete such tasks is critical to maintaining our national economic competitiveness and security. However, automated manufacturing system integration is a complex cognitive skill that typically takes years to master. To better prepare engineers and manufacturers to compete in a rapidly changing world, needed is a better understanding of the nature of system integration skill and how to acquire it.

This study reports preliminary observations from a verbal protocol analysis study of expert and novice system integration engineers. Subjects included four application engineers from an engineering services firm (all with 15 or more years of system integration experience) and two early career engineers with four or fewer years of experience. All were asked to design an automated cell phone assembly line given a set of seven parts, a $1M budget, a six-second cycle time, and nine months to complete the project. The subjects were asked to think aloud as they came up with design alternatives.

Background

Over the past few years, we have interviewed system integration engineers from 17 companies throughout the U.S. These interviews were conducted in two rounds. The goal of the first round of interviews was to get the "lay of the land" in terms of:

- What is a typical project like?
- What types of projects come up most frequently?
- What is your role?
- What are some of the constraints that you typically face?
- What tools or resources do you use to solve problems?

One observation from the first round of interviews was that system integration engineers generally work in teams and can be classified into one of three job types: application engineer, control engineer, and mechanical engineer[1]. Application engineers tend to be the most experienced. Their job is to come up with a conceptual design for an automated system based on a customer's requirements. It is typically their responsibility to develop proposals and to communicate design information to customers and other members of their team.

During the second round of interviews, we have continued to ask experts about their jobs and the system integration industry, with a particular focus on application engineers. We have added an exercise in which they are asked to come up with a design for an automated assembly line while thinking aloud. Depending on the background of the engineers, one of three design exercises are used: cell phone assembly, truck frame assembly, or airline seat assembly. This paper reports preliminary results for engineers solving the cell phone assembly line design problem. The goal of the analysis was to begin to characterize the types of knowledge expert application engineers possess and how they solve automated manufacturing system design problems.

Method

Subjects. Subjects included four application engineers from a engineering services firm (all with 15 or more years of system integration experience), one engineer from the medical devices manufacturing industry with four years of experience, and one engineer from at an air conditioning manufacturing company with two years of experience. The four application engineers all have 15 or more years of system integration experience and are considered to be experts by their peers. The latter two engineers work with automated manufacturing systems, but have little system design experience; we consider them to be novices for the purposes of this investigation.

Procedure. The interviews were conducted as follows. The interviewer would:

1. Introduce himself and describe the purpose of the interview (to gain a better understanding of system integration)
2. Show the engineer a cell phone assembly consisting of eight parts (see Figure 1).
3. Ask the engineer to think aloud about how he would go about designing an automated system to assemble a phone from these parts, given a $1M budget and a six-second cycle time (i.e., at least one phone needs to be produced every six seconds). The requirements were purposely stated rather broadly to allow us to better understand what the engineers would want to know. When the engineers would ask for more information, the interviewer provided it. The engineers did not all request the same types of information, but if more than one engineer asked the same question, an effort was made to provide a consistent response.
4. In addition to the think-aloud, if time permitted, the interviewer also asked questions such as:
   - What types of automated systems have you worked on?
   - What types of projects come up most frequently?
   - What types of problems do you encounter most frequently?
   - What are the most critical types of problems you need to solve?
   - What resources do you use to solve problems?
   - Tell me about a typical project that you've worked on recently.
   - What was your goal?
   - What were your constraints?
   - What types of problems did you need to solve?
   - For each problem:
     - What steps did you follow in solving this problem? Indicate decision points. Draw a diagram if appropriate.
     - Did you work on a team? If so, what was your role?
     - What type of system integration problems do new engineers typically have the most trouble with? Why?

A significant challenge to the data collection process was that application engineers are typically the busiest members of system integration teams, because they are needed to help bring in new business. They were usually interviewed at their work sites and the time available to interview them was limited to 60-90 minutes. As a result, the interviews were more rushed than the ideal.

Figure 1. Cell phone parts used in conceptual design think-aloud exercise

Analysis Methods and Results

In qualitative research, transcripts provide a rich source of data. The challenge is to figure out how to analyze the data in a way that is both systematic and meaningful. In this case, the overall goal of the analysis was to begin to characterize the types of knowledge experts possess and how they solve automated manufacturing system design problems. We did this by 1) noting the types of questions that the engineers asked during the conceptual design exercise; 2) studying how engineers approached designing for the various assembly tasks, in terms of the kinds of statements they made; and 3) making general observations about the comments that were made during the interviews.

Analysis 1: Questions asked

The goal of this analysis was to characterize the types of information that system integration experts seek out in making design decisions. Our hypothesis was that the types of questions they ask would be different from those asked by less experienced engineers.

Engineers were asked to think aloud about how they would go about designing an automated system to assemble a phone from these parts, given a $1M budget, a six-second cycle time (i.e., at least one phone needs to be produced every six seconds), and nine months to complete the project. In real life, engineers typically receive a written specification before beginning a design task. For the purposes of this investigation, however, the requirements were stated broadly, at least initially. This allowed us to better identify the types of information the engineers felt they needed to know. Table 1 summarizes the types of questions that were asked. Note that for the purposes of this tally, a “question” is considered to be either an interrogative statement or a declarative statement that this type of information would normally be available.

	NOVICE		EXPERT			
	N1	N2	E3	E4	E5	E6
1. Do any of the parts need to be made?	x	x				x
2. How much do the parts weigh?	x					
3. Do I have my own work area?		x				
4. Is there a written specification available?			x	x	x	
5. Are part drawings available?			x	x	x	
6. What exactly is included in the cost?					x	
7. Does the assembly line need to be able to easily modified to accommodate product design changes?			x		x	x
8. What exactly is due at the end of nine months? What are the milestones?			x	x		
9. To what extent will human operators be involved in the assembly process?			x	x	x	x
10. Exactly what pieces are included in the assembly process?			x	x	x	
11. What is sequence/process of assembly?			x	x	x	x
12. How are pieces held in or held together (e.g., snapped in, adhesives, welding)?			x		x	x
13. How are parts presented (e.g., on a tray, on a strip, in a feeder bowl)?			x		x	x
14. Are inspections/testing required during the assembly process?			x	x	x	x
15. Does screw torque and angle need to be monitored?			x		x	x
16. Does the customer have any special quality requirements (e.g., no scratches, no skewing)?			x		x	
17. When inserting screws, how much torque is required?			x		x	x
18. Are the screws all the same size?						x
19. Does the order in which the screws are inserted matter?						x
20. Does the customer have any requirements about handling of rejects or make up stations?			x	x	x	x
21. Does the customer have any product tracking requirements? (E.g., is bar code scanning required?)?			x	x	x	x
22. Does the customer have any requirements related to keeping the work piece free of debris? (E.g., is a clean room required? Should certain parts not be touched?)			x			x
23. Does line run continuously? How much down time is expected?				x	x	
24. Are there any other special considerations? (E.g., the equipment must be from a certain manufacturer)			x	x	x	x

Table 1. Questions asked by novice and expert engineers during think-aloud design exercise.

Following are some observations based on Table 1.

1. The experts asked more questions about the task than the novices; they appear to want more information before making a design recommendation.
2. The experts tended to ask about the same things; i.e., they had similar concerns.
3. The experts' questions were aimed at identifying or clarifying client requirements over and above meeting cost, cycle time, and deadline targets, such as:

   - Does the customer have any requirements related to avoiding scratching or marking the product?
   - Does assembly have to take place in a clean room?
   - Does the customer want to include inspection stations at certain points in the assembly process?
   - Will human operators be participating in the assembly process? If so, how many?
   - Is there a requirement to use specific vendors and/or brands of equipment?
   - Does the line need to be able to accommodate changes to product design in the future?

Analysis 2: Designing for specific assembly tasks

The goal of this analysis was to characterize how expert system integration engineers think about conceptual design. To make the analysis more manageable and to facilitate comparisons between engineers, we broke the think-aloud transcripts into sections based on the assembly line tasks the engineers needed to automate. In the case of the cell phone assembly line, the engineers needed to come up with ways to handle the following tasks:

1. Present liquid crystal display (LCD) housing.
2. Present/insert keypad.
3. Present/insert switch.
4. Present/insert circuit board.
5. Present/insert casing.
6. Present/insert screws.
7. Present/insert battery.
8. Present/attach back cover.
9. Present/attach antenna.

Note that the tasks don't necessarily need to be completed in the sequence given above; for example, an engineer could choose to work on two sub-assemblies in parallel and then merge them later. However, all tasks need to be accounted for at some point in the assembly process. Also note that this list represents the *minimum* number of tasks that need to be accomplished in order to assemble the phone. A real-life customer scenario would likely include many additional requirements, such as quality checks and provisions for handling products that fail to meet quality standards (such as makeup stations).

Following are observations from a task-by-task analysis of the data. To support these observations, we will provide examples of how the engineers designed for Task 6, presenting and inserting the screws. This task involves sealing the main phone assembly by inserting five small screws. As a reminder, the engineers were asked to design an assembly line that could produce one cell phone every six seconds.

- *The novices were more likely to omit tasks or need prompting to remember to address tasks.* For example, N2 did not provide a method for presenting screws; he stated only that "there would be some sort of drill type of machine with magnetic type of drill in it which is on some sort of robot or a moving machine which puts them in."

- *The novices were more likely to suggest unrealistic ways of accomplishing a task.* For example, N1 stated that the screws would be presented face down for a robot to screw them in. When asked how that would happen, he said that he would try to order screws from vendors that are packaged face down.

- *The novices were more likely to focus primarily on the mechanics of the assembly line design.* They tend not to mention considerations or constraints other than those provided in the scenario. In contrast, the experts were more likely to raise issues that are not presented in the scenario. For example, all four of the experts stated that there would also usually need to be a way to check the assembly after the screw insertion task for problems such as skewed or missing screws.

- *The experts were more likely to provide commentary while describing their designs*, such as design rules of thumb and details about what clients usually want in similar situations. For example, E3 opined that "when you drive screws, most of the time the customer is going to want to monitor the torque. That proves that he has gotten the screw all the way in and you don't strip the screw—that's what the angle is for." (suggests that…)

- *The experts were more likely to suggest more than one way to accomplish a task.* For example, when discussing how the screws would be presented, E4 states: "You would probably put the screws in a small bowl…And that bowl would orient those screws, and you would probably blow feed them right into a screwing head. You blow them in there and they go right into the screwing head and right into the product. I don't know if this is a candidate for that, so I may talk to that manufacturer to see if you can do that—I doubt it, it's pretty heavy—but that's a possibility. The other possibility that I drew here is you could certainly—and it's not that top heavy—you could feed this in bowl and they could be coming out like this. So you've got a bunch of them. (*drawing*) Like that. Coming down a track. So I've got to have some kind of device that comes down and gets one. I may need a device that separates the last one out."

- *The experts mention more details in their designs than the novices.* For example, in describing the insertion of the screws, N2 states that "there would be some sort of drill type of machine with magnetic type of drill in it which is on some sort of robot or a moving machine which puts them in." In contrast, E6 states that "It looks like I should be able to drive all five screws at once, something that I have to check to make sure to get the mantle of the screws in there. I would prefer to drive all of them at once if I can. I can see…five individual screw drivers though, but they're on a mechanism so they can run on the counter weight. Each screw driver would then…monitor the torque angle and the distance."

Analysis 3: General observations

This section presents general observations about how the expert and novice engineers approached the conceptual design task.

- *All the experts and one of the novices noted that they would work closely with equipment vendors to identify the best equipment to accomplish tasks. However, the experts seemed more familiar with available equipment, in that they were more likely to suggest using special or specific types of tools.* For example, when describing the equipment he would use to insert the screws, E5 stated: "You'd buy a Weber screw driver. It has a feeder system that would blow a screw down the tube right into a driver, and then the driver moves in, drives and come back."

- *The experts all mentioned high-level design considerations not included in the cell phone assembly scenario*. Specifically, all four experts considered whether to use synchronous or non-synchronous approaches in their line design. A synchronous approach employs hard tool automation such as a cam-driven chassis to drive the process. All tasks on the line require the same amount of time to complete. A non-synchronous approach employs programmable automation such as robots. As a rule-of-thumb, synchronous assembly lines have a higher set-up cost, but are very fast. A non-synchronous line would be less expensive for this type of application but would be slower. However, the principal benefit is that they are flexible. Robots can be quickly reprogrammed to accommodate changes in assembly processes, which is important when manufacturing rapidly changing consumer electronics products such cell phones.

- *The experts drew different conclusions and produced different designs.* Interestingly, although the experts asked similar questions and considered similar issues, they did not all reach the same conclusions. For example, even though all four experts considered both synchronized and non-synchronized approaches and exhibited a similar understanding of the advantages and disadvantages of each approach, E3 recommended a synchronous approach, while E4, E5, and E6 all recommended a non-synchronous approach. E3 believed that a non-synchronous line would probably not meet the cycle time target of six seconds per phone. The other three thought a non-synchronous approach would meet or come acceptably close to meeting the cycle time requirement. (might be due to lack of a written spec)

- *Both novices and the experts use commonly available resources in working on design-related tasks.* The experts used commonly available resources to do their jobs—the web and the telephone to get information about equipment capabilities from vendors, standard office applications (such as Word, PowerPoint, and Excel); and 3D mechanical design and modeling software (such as SolidWorks). Because their job involves generating proposals for clients, the experts were able to work from templates in calculating costs and putting proposals together.

- *The experts' design solutions are strongly influenced by business needs such as the need to bring in contracts and to finish them within budget*. For example, E4 notes that "a lot of times [what] the students don't have a feel for is—you're competing also. So you can't… Like I say, you've got that ceiling of a million dollar budget, you could have the best solution out there, and if it cost 1.2 million dollars, you're not going to get the work. So we've got to be competitive also."

- *The experts are very sensitive to customer needs and requirements*, as evidenced by their questions and their frequent mention of "the customer" both during the think-aloud exercise and when answering interview questions about their work. They all emphasized the need to listen to the customer and to learn as much as possible about the customer's requirements throughout the design and proposal development process. For example, E6 notes that: "I like to get to a point where I got all three pieces—my write-up, my layout and my pricing, as far as a first pass where I feel like I'm 90% done—I like to go and review it with upper management. I like to even touch base with the customer, you know walk him through as I'm developing this, to keep his input cause ultimately he's the one that's got to…it's his process and I want to make sure that I'm assembling this product correctly to his process. So if I got a station like with your circuit board, um…is there a special way we've got to handle that? And this is maybe to let him know this is how we're handling it now, do you see a problem? If not, then I go ahead and head in that direction. There is nothing worse than going out to a customer site and present him with a proposal and you're mishandling his parts. So there is constant communication between the customer and myself."

Discussion

This section describes some possible implications of the findings described above.

<u>What is the goal of expert performance in the area of conceptual design of automated systems?</u>

The goal of an expert applications engineer appears to be to come up with a conceptual design that addresses the client's requirements while allowing the engineer's employer to make a profit. In other words, the design needs to be do-able within the proposed cost and time constraints. Often this means reusing successful approaches from other similar projects and/or utilizing commercial off-the-shelf tools and equipment as much as possible.

This is not to say that the experts aren't inventive. One of our interview questions was "What was the most difficult project you've ever worked on, and why?" The responses that we have heard so far suggest that the experts are inventive people. However, out of practical necessity, they avoid pursuing innovation for its own sake. As one engineer (E4) pointed out, "There is always risk associated with original design."

<u>What do expert system integrators know?</u>

Expert system integrators have extensive experience with one or more types of automated systems. (Note that it is possible to be expert in certain types of automated systems, such as systems for discrete processes, like assembly, and not expert with other types, such as continuous systems used in the refinery industry.) For the systems they have expertise in, they possess a wealth of specific declarative and procedural knowledge about things such as the processes that need to be automated, the equipment and tools usually used, and control strategies. This knowledge helps them to know what is needed to automate a particular process, and to evaluate the advantages and disadvantages of various design decisions.

Although they know quite a bit about equipment and tools, they also freely admit that they rely on vendors for specifics about equipment and tool capabilities, precise cost information, and information about new products.

They have rule-of-thumb knowledge how long it takes and how much it costs to do things—enough to evaluate and compare various design options. However, they rely on vendors and their co-workers for specific time and cost estimates.

They have knowledge about how to work with clients on projects—such as what clients usually want and need, what questions to ask, and what needs to be done to make sure the project meets the client's needs. One might even say they have schemas for successful interaction with a client.

They know how to work with their own team—such as how to communicate ideas and goals to team members, and how to tap into their team members' expertise.

How do expert system integrators think?

When developing a conceptual design for a new automated system, the expert system integrators in this study strive to come up with a design solution that meets customer requirements while allowing their company to make a profit. This means that they are very sensitive to customer needs. Typically they are given a written specification and drawings to work from, but they also interact with the customer frequently during the conceptual design process to make sure they are designing an appropriate solution. In developing proposals, the engineers draw upon their own and their colleagues' experience, and ask equipment vendors for information about the availability and capabilities of commercial tools and equipment. They also use proprietary spreadsheets and proposal templates.

The way these expert system integrators work with their customers is reminiscent of the cognitive script concept advanced by Schank and Abelson[3,4].. Scripts are hypothesized cognitive structures that when activated, help humans to comprehend and to know how to behave in event-based situations, such as dining at a restaurant. Scripts are made of slots and requirements about what can fill those slots. So, for example, when dining at a restaurant, the slots in a restaurant script help you know to expect someone to ask for your order and how to respond appropriately. Scripts may also have tracks, such as a fast food track or a fine dining establishment track in the restaurant script. In the case of system integration, it appears that an application engineer's interactions with a customer are script-based, in that the engineers seem to know to ask the customer for certain types of information. One could even say that the engineers in this study were working from a consumer electronics track of an assembly line design script.

Assuming that system integrators' design behavior is script-based allows us to explain a few things, such as the reason why they ask so many questions—presumably they are trying to fill in slots of expected information. It also explains how they are able to come up with designs so quickly (typically within 3-4 weeks, while working on other projects as well), because they know the right questions they ask to get the information they need. Third, it may explain why they tend to stick to "tried-and-true" problem-solving approaches, such as using spreadsheets, rather than using newer technologies, such as simulation tools—because the script does not have a slot for that. Finally, although we don't have direct evidence for this, relying on scripts may also restrict their ability to "think outside the box" when developing new designs.

Scripts may not explain how system integrators are able to come up with new designs. However, based on our observations, our hypothesis at this point is that they often refer to previous systems that they have worked on or seen in coming up with designs. They appear to be looking for solutions to similar problems. They also rely heavily on vendors to help them to identify equipment that could help them to perform a particular task. It appears that the design of an automated assembly system can be viewed in terms of coming up with ways to automate multiple small tasks. Integrating the stations that perform these smaller tasks is primarily a matter of making the connections and adjusting the timing so that tasks get completed in time for the next task (i.e., line balancing).

How might we help engineering students to develop system integration design skills?

Most of the expert engineers that we interviewed maintained that their skills were developed through years of experience in building systems, and that new engineering graduates cannot be expected to be able to design systems, let alone do it well. However, we believe that even though new engineers would not typically be responsible for designing systems, they should have a general understanding of what goes into developing an conceptual design. An introductory course on system integration (offered to upper-level undergraduates or to graduate students) might accomplish this by requiring students to 1) study different types of automated systems in depth to understand how they work and why they were designed the way they were; 2) role-play interactions with a client; and 3) build simple automated systems based on client specifications. If possible, this course should provide students the opportunity to build at least one operational automated system. In addition, to provide more opportunities to practice, we are also developing a prototype web-based Automated Assembly Line Design (AALD) environment that students can use to build and compare designs for a virtual assembly line. The AALD environment is described in detail in the Activities section of this report and will be evaluated in the next year of this project, both by students for instructional effectiveness and by expert system integration engineers for fidelity and accuracy.

Future Directions

Possible future directions include:

- Continued analysis of the interview and think-aloud data that we have collected thus far. Although the data collection conditions were less than ideal, the interview data are very detailed and provide a rich source of information about the system integration industry. We plan to analyze data from the airline passenger seat and truck frame assembly line design exercises to see if the observations we're made so far continue to hold up. We would also like to learn more about strategies applications engineers use to reframe the design problem when they can't come up with a design that meets all the customer's requirements (for example, one possible solution is to ask the client to redesign the product).

- Conducting another think-aloud study of experts using a more elaborate and comprehensive specification and more realistic role-play. This may help us to better understand why different experts come up with different designs.
- Developing a library of automated systems for use as a learning tool and reference.

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Bibliography

1. Hsieh, S. "Automated Manufacturing System Integration Education: Current Status and Future Directions," *Proceedings of 2005 ASEE Annual Conference, June 12-15, 2005, Portland, OR.*
2. Schank, R.C. and Abelson, RP. (1977). *Scripts, Plans, Goal and Understanding: An Inquiry into Human Knowledge Structures*. Hillsdale, NJ: Erlbaum.
3. Abelson, R.P. (1981). Psychological status of the script concept. *American Psychologist*, 36, 715-729.