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Modeling in a University-Industry Collaboration: Deep and Surface Approaches

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Introduction

Engineering in the workplace often requires interdisciplinary teams to address ill-structured and complex problems [1], where experienced designers use multiple ways to communicate their design ideas that allow for deep inquiry into a design scenario [2]. These forms of communication include sketches, diagrams, and models [3]. Moreover, successful teams are apt to share *mental models,* or shared knowledge structures that allow a team to coordinate actions and adapt their behaviors [4], influencing both design product and design process [5] [6]. However, there is a lack of data regarding how successful interdisciplinary teams address a common, urgent design goal.

This research investigates how individuals in an interdisciplinary team approach mental and physical models to address a common goal. Deep modeling is understanding how a device functions, the constraints of a project, and the dynamics of effective team collaboration. In contrast, surface modeling is a less experienced and less effective approach to a design project where designers tend to propose superficial ideas or use ineffective means to communicate how a system works.

Background & Motivation

In December 2019, COVID-19 became a threat in the United States and began to change how life would be lived. Being able to verify infection status is important for slowing the spread of the virus in, and between, communities [7]. COVID-19 testing protocols were quickly implemented across the United States, with colleges, and schools in general, being important locations. These diverse locations saw traffic from various areas of the country, which could create the potential for outbreaks of the virus. The University of Illinois at Urbana-Champaign put together the mobile SHIELD project.

The mobile SHIELD project was a mobile laboratory designed to serve COVID-19 diagnostic testing needs across the country where infrastructure lacked the ability to have testing centers, or where new outbreaks emerged and more testing volume was needed [8]. A team was put together that consisted of various disciplines, including lab and testing, system design, data and information technology, finance, community outreach, and project management. This diversity was intentional to promote unique ideas. However, the varying degree of design experience and members living in multiple time zones both created conflict and added complications to the design process. The use of technology to communicate with team members all across the country became essential for success. "Technology also facilitated communication, collaboration, and productivity. Team members felt more comfortable asking questions and sharing information through an instant messaging platform, i.e., Slack, compared to sending an e-mail [8]. The team used both cloud-based file sharing methods and collaborated with physical prototypes, so there were multiple forms of team models.

The goal of this exploratory study was to analyze post-project interviews transcripts to categorize how team members experienced deep and surface modeling in their work.

Literature Review & Theoretical Framework

Informed Design and Modeling
The Informed Design Teaching and Learning Matrix [2], herein referred to as "the Matrix," is a framework to examine how nine key design strategies are employed by expert designers compared to more beginning designers. The Matrix deconstructs the design process to explain the productive design behaviors continuum better.

One design strategy discussed in the Matrix, "representing ideas," is essential in effective design processes, and the pattern of "surface versus deep drawing and modeling" is evident in design products. In order to develop a prototype, a designer needs to develop a deep understanding of how it will function. While an idea may seem perfect in the ideation phase, it may lack the ability to be realistically implemented, or it can be too ambitious for a design constraint such as budget. Furthermore, deep drawing and modeling require attention to detail for each functioning sub-design of the prototype. Goel and Pirolli [9] describe this important step in the design process by saying,

> "Being large and complex, design problems have many parts. Nevertheless, there is little in the structure of design problems to dictate the lines of decomposition. Decomposition is substantially dictated by the practice and experience of the designer" [9].

When an experienced designer with deep drawing and modeling techniques works through designing these decomposed parts, the sketching process is more sophisticated than a beginner or more inexperienced designer. The experienced designer is apt to spend more time in the sketching phase of the design process as the visual representations become more technical as ideas progress and develop.

> "Initially, the use of quick sketches, rough calculations, and intuitive scribbling of forms and shapes helps engineering designers to translate emergent images in the mind's eye into tangible forms. The very act of drawing helps to clarify their understanding of the dimensions of the engineering problem, determine how they might set about resolving them and to bring tentative solutions to the surface of the mind," [10].

Expert and effective designers tend to explore and represent their design ideas with "multiple representations" to explore their design ideas more deeply. In turn, this deeper modeling allows the designer to explore how the overall system works [2] by accounting for the interactions between components. In contrast, less experienced designers propose "superficial ideas" that might not work if built [2] and do not account for interactions between subcomponents that shape system behavior and outcomes.

Team mental models
While the Matrix explicitly addresses individual design behaviors, designers and engineers often work in teams, and therefore team behaviors are also crucial in project success. A synthesis of team effectiveness theory suggested the importance of shared mental models for understanding the effectiveness of design teams [4]. Borrego and team lean on an earlier definition from Cannon-Bowers and team [4] that shared mental models are shared "knowledge structures that enable a team to form accurate explanations and expectation of the task, to coordinate their

actions, and to adapt their behavior to demands of the task and other team members" [4]. The degree to which a team shares mental models tends to impact team success [5] [11] [12] [13] [14] and is especially important for interdisciplinary teams [4].

Methods

Context & Sample

This exploratory study was conducted with a university-industry collaboration at the University of Illinois at Urbana-Champaign that designed a mobile laboratory to address the need for COVID-19 diagnostic testing using a saliva-based, University-developed Polymerase Chain Reaction (PCR) test during the July 2020-December 2020 timeframe of the mobile SHIELD project. The mobile component was the essential differentiator to help increase the utility of the testing by allowing a mobile unit to deploy to remote locations with sites for specimen collection, collection device, the actual lab, and the information management system. To accomplish this innovative design goal, the team included interdisciplinary members from the following focus areas or "thrusts": Lab and testing, Data and IT, Finance, System Design, Community Outreach, and Project Management.

Data Collection

After obtaining IRB approval, we conducted semi-structured interviews with 18 members of the SHIELD team online via Zoom to better understand their approach to and how they engaged with the design process, including their work system and contributions to the overarching need for increased access to COVID-19 testing. In this study, we chose to include data from seven of the eighteen members because of their involvement with both mental and physical models during the planning and implementation processes as evidenced from their transcripts. Participants were from the following thrusts: Lab and Testing (n=3), Data and IT (n=3), and System Design (n=1). Each interview was audio recorded through Zoom and transcribed by a professional transcription service (See Authors, 2021 for the interview protocol.) In total, the 7 transcripts comprised 401 minutes of audio data for approximately 57 minutes per interview.

Data Analysis

We performed a thematic analysis [15] to categorize how team members exhibited behaviors that could lead to either deep or surface modeling in their work. The first author led the primary coding, starting with deep modeling versus surface modeling. The second author reviewed and discussed the first set of codes. Next, the first author used a deductive approach to further refine each deep modeling and surface modeling theme into more distinct units for primary categories of codes. In our coding scheme, codes were exclusive such that each transcript excerpt could only have one sub-code theme. The first set of codes, deep vs. surface modeling, was inspired by the Informed Design Matrix [2]. The secondary coding category was developed deductively from the transcripts and included the category of shared mental models developed from the transcripts and supported by Borrego and team [4]. The code for shared mental models described excerpts that explicitly addressed shared structures that allowed the team to coordinate actions and adapt their behaviors where inhibited mental models describes the instances that led to less effective shared understandings of the project. The second author reviewed all of the transcripts independently with the secondary codes. When there was disagreement between researchers on a transcript, the resolution included re-reviewing the transcript and discussing the difference in opinions until a consensus was agreed upon.

Results & Discussion

Results of the thematic analysis suggest that SHIELD team members engaged in behaviors that are conducive to deep and behaviors that might lead to surface modeling (see Table 1). Table 1 represents each case, or project team member, with the instances of deep or surface modeling in their interview transcript. This section will be organized with explanations of the sub-themes within the two main themes of deep modeling and surface modeling. Of the total 39 excerpts coded from the seven transcripts, 30 represented deep modeling while 9 represented surface modeling. Codes were mutually exclusive such that each excerpt only represented one code. Excerpts from the transcripts are included to illustrate the context, identified by Project Team Member 1 through 7.

	Deep							Surface	
People	Understanding the Challenge	Shared Problem Frame	Understanding Feasibility	Create Project Sub-Divisions	Shared Models	Iteration	Prototype and Test	Lack of Understanding	Inhibited Shared Mental Models
Project Team Member 1	x	x	x	x		x	x	x	x
Project Team Member 2	x	x	x			x	x		
Project Team Member 3	x	x				x	x	x	x
Project Team Member 4	x	x		x		x	x	x	x
Project Team Member 5		x	x		x	x		x	
Project Team Member 6	x	x	x						
Project Team Member 7	x				x		x	x	x

Table 1: Deep versus Surface Coding Matrix

Theme 1: Deep Modeling

Within the category of deep modeling, team members demonstrated sub-themes of: understanding the challenge, shared problem frame, understanding feasibility, creating project sub-divisions, shared models, iteration, and prototyping and testing. Notably, all seven transcripts included instances of each deep modeling sub-theme, as further described below.

1a: Understand the Challenge

This sub-theme means team members conducted initial research and/or investigation into what their task asked of them. Having an initial understanding of the project was a deep modeling characteristic seen in six of the seven interviewee cases. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"What we did, initially, just did an evaluation of what's out there, and what can we use? What open sources are out there? What works? What doesn't work? That's what we did initially."(Project Team Member 7)

"My original task was more information finding…I had some opportunity to actually work for brief periods of time within the lab, so it gave me kind of first-hand understanding of kind of like the day-to-day process and what do people do. I think it's very important to have that perspective. Because if you don't have that perspective, then it's kind of a black box, and you don't really know exactly what's going on."(Project Team Member 4)

1b: Shared Problem Frame

This sub-theme means that team members defined criteria and constraints of the system and delayed decisions until they shared an overall understanding of critical elements rather than jumping immediately to problem solving. Informed designers "delay making design decision...in order to frame the problem better" [2]. In a team setting, this shared problem framing is essential to collaborative design. Having a shared project frame was a deep modeling characteristic seen in six of the seven interviewee cases. This sub-theme was tied with '1a: Understand the Challenge' for being the most observed. Two representative quotes are included to better demonstrate how these team members approached understanding the project, especially focusing on criteria for success.

"This is one where everybody is coming from different backgrounds, but they're all after the same goal. And you usually don't see that, so that's impressive."(Project Team Member 2)

1c: Understanding Feasibility

This sub-theme means team members contemplated if a design would be possible to create within the constraints of the project. Constraints could include time to complete, cost of production, and existence of technology. This is opposite of how Crismond and Adams describe beginner designers. "Beginning designers may produce no drawings or faulty ones because they lack the requisite graphic fluency in sketching, which 'requires considerable skill'. They have patchy or inaccurate device knowledge, ignore constraints, and create proposals that could not be realized as actual products," [2]. Understanding feasibility was a deep modeling characteristic seen in four of the seven interviewee cases. Three representative quotes are included to better demonstrate how these team members approached understanding the project.

"The second concept was coming up with a box van, which we would see on the highways like an 18-wheeler, and then fitting the lab in there. So now you go from the vet lab, which has various rooms and multiple opportunities for enhanced square footage, now you go into a 48 x 12-foot, which is what's on campus now. Then you go to a 50 x 8-foot. So you're slowly shrinking your footprint down, and you're still supposed to have the same output. So that challenge was, design that"(Project Team Member 2)

"You're 6' 2". All right, now [Project Team Member], you go use the same work station. You're 5' 2". So we were trying to account for variation throughout the process physically, thinking about the design in terms of talking with people who had designed mobile kitchens"(Project Team Member 1)

"For me, these diagrams, it was trying to map what was happening in real life with where things were going to show up in the data base schema."(Project Team Member 5)

1d: Create Project Sub-Divisions

This sub-theme means that team members broke the project down into organized and logical sections. The creation of subsystems allowed team members to systematically work through the problem and split up the work load, and was the general structure of the project with "thrusts." Furthermore, "research findings reinforce the idea that team processes aligned to team goals ensure team effectiveness," [4]. Creating project sub-divisions was a deep modeling characteristic seen in two of the seven interviewee cases. Data & IT was the only thrust to not display this sub-theme. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"So at first, I started thinking about the project in kind of four main areas. One was the part that had to happen in the lab, the testing, the financial piece that would make all of this economically feasible, the data and IT structure, and then kind of the humans and the overall system"(Project Team Member 1)

"It would have been impossible without the number of specialized people, whatever they were doing. Right? We had communications people. We had transport people. We had computer people. We had molecular people. We had the Veterinary Diagnostic Lab. We had the personnel."(Project Team Member 4)

1e: Shared Mental Models

This sub-theme means that team members formed, "accurate explanations and expectations of the task, to coordinate their actions, and to adapt their behavior to demands of the task and other team members," [4]. Additionally, "the concept of shared mental models is useful in understanding how teams approach complex, ill-defined projects, and may be particularly useful for understanding interdisciplinary team effectiveness" [4]. Having shared models was a deep modeling characteristic seen in two of the seven interviewee cases. Interestingly, this theme was only evident in the Data & IT thrust interviews. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"I also remember seeing all those diagrams start showing up in the Box website and going through those and having a few lightbulbs go off"(Project Team Member 5)

"And then around the time I got done with that, [Project Team Member] had sort of started, he, so the core first piece of information I had that was really useful was what [Project Team Member] said were his chicken scratches on a piece of graph paper" "But that, yeah, [Student] and [Project Team Member] and I don't know who else from your team, you generated like just a ton of like workflow diagrams. And I'm sure you have names for all of these different things, that I'm completely ignorant of, that were just super helpful. Just to kind of like, it was just mapping out all these different aspects of how to look at the process"(Project Team Member 7)

1f: Iterate

This sub-theme means that team members improved designs over many different versions to create a more refined product. Iterative design, sometimes described as feedback loops, is considered an "integral feature" and "natural attribute of design competency" [2]. Iterating was a deep modeling characteristic seen in five of the seven interviewee cases, including all three of the lab and testing team members. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"And as we were building it up, we're realizing, okay, this isn't going to work. That's not going to work. And then we just had conversations. How would you do this better? Why would you look at it this way? Why would you? We've had ten iterations of tube rack designs, because every time

we come up with something, somebody else looks at it, or we run practice like, well, maybe we should do this, change this. Maybe we don't need to do, put it in a bath. Maybe we can use it here and just, we change materials. And that's pretty much how, it's kind of the scientific process"(Project Team Member 2)

"And so you really need to design the process. Then you design the facility. Then, and it's all an iterative process. It was a very iterative process, again. And so we started with designing, we started with not knowing anything. And so we got an initial set of information from the, from DVL. And then as we kept on asking questions, we kept on finding new things and asking additional people. And so we started being able to drill down and understand what we needed in each one of these operations"(Project Team Member 3)

1g: Prototype and Test

This sub-theme means that team members developed different representations of their ideas and then tested them to become closer to solving the design problem. "Informed designers use gestures, words, and artifacts to explore and communicate their design plans. They make drawings, construct physical prototypes, and create virtual models that help them develop deeper understandings of how their designs function," [2]. This differs from the sub-theme of iteration in that while this theme depicts testing and evaluating of an idea, there are not necessarily connected steps to make changes or improvements. Creating a prototype and conducting testing was a deep modeling characteristic seen in five of the seven interviewee cases. A representative quote is included to better demonstrate this theme.

"And we like laid everything out, physically, what the lab would look like, and then kind of walked through it just to see what the process would look like." "Yeah. And by that point, we were like, okay, we need to do a lab prototype, you know, just a prototype app. So then it was where we, I pulled in a guy from my group and another developer. Like we're just going to write this prototype. And then we had lots of discussions over Zoom and in Slack and whatever just talking through what the screens might look like"(Project Team Member 7)

<u>Theme 2: Surface Modeling</u>

Within the category behaviors that could lead to surface modeling, team members demonstrated sub-themes of: a lack of understanding and inhibited shared mental models. Contrary to the deep modeling sub-themes, surface modeling surface modeling is a less experienced and less effective approach to a design project where designers tend to propose superficial ideas or use ineffective means to communicate how a system works.

2a: Lack of Understanding

This sub-theme means team members did not conduct initial research and/or investigation into what their task asked of them. Crismond and Adams explain that, "when operating with little functional knowledge of the device, they can generate plans that focus 'almost entirely on aesthetic features,'" [2]. Lacking an initial understanding of the project was a surface modeling characteristic seen in five of the seven interviewee cases. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"Well, I think it would have helped, if I look back at what I wish I had initially is, I think I should have staffed more scientific people, that actually understood the laboratory."(Project Team Member 3)

"Because we just didn't, I don't think that we expected that we would have that short amount of time and that many of samples often. Right? So I think we budgeted. Okay, we theoretically should be able to do 20,000 samples per day. Right? That's all the calculations. But I think that doing something on paper to say how long does it take for a thermocycle to run that reaction time is very different than when you're actually doing it"(Project Team Member 4)

2b: Inhibited shared mental models

This sub-theme describes the instances that led to less effective shared understandings of the project. In these instances, team members had difficulty sharing ideas between each other, or lacked a consistent method of communication, which is a characteristic of a less mature, or surface, designer. A strong shared communication method, on the contrary, is capable of, "enabling problem scoping and solution archiving by enhancing collaboration and communication," [2]. This project was initiated during a pandemic at the height of emergent remote work situations, and difficulty with communication was a surface modeling characteristic seen in four of the seven interviewee cases. Two representative quotes are included to better demonstrate how these team members approached understanding the project.

"[Student] and myself would be asked, you know, to kind of review data electronically, but we weren't meeting together to talk about the data. It would be more often that, oh, we got these results. What do you guys think, you know? How could we optimize? How do you interpret these results? Instead, there was an open digital forum for us to communicate, but there wasn't really a structured every, you know, day of this week at this time we meet to discuss, we didn't have that."(Project Team Member 4)

"But there is some cost to not being able to talk to somebody in person. I think some of the political maneuverings and whatever takes a lot longer just because we're all kind of missing each other a little bit in email or whatever and so that adds some load. But overall, I think it has actually been better. I don't know that most people would agree with that, but I kind of have."(Project Team Member 7)

Informed Design Team

The mobile SHIELD project was by all accounts a successful design and team implementation [2] [3] [4] [5]. Techniques associated with these experienced designers engaged in deep modeling likely benefited the mobile SHIELD project. In particular, all team members individually demonstrated sub-themes of understanding the challenge, shared problem frame, understanding feasibility, creating project sub-divisions, shared models, iteration, and prototyping and testing. These sub-themes encouraged a more comprehensive understanding of the project and saved time by helping avoid unnecessary setbacks. Rather than ignoring constraints and spending little time doing preliminary design, these team established common mental models through shared goals. This approach is supported in the literature as "team processes aligned to team goals ensure team effectiveness [11]" [4]. Attending to team processes such as the sub-themes identified in this work may have a more significant impact on outcomes than focusing on fixed inputs, such as personality types [4]. However, the successful team had opportunities to approach communication in in subthemes of a lack of understanding and inhibited shared mental models in order to further improve their overall team design process.

Conclusion and Future Work

This work-in-progress showed one approach to understanding a successful university-industry design team: through the extent to which they engaged in deep modeling practices. The multi-disciplinary team working on the mobile SHIELD project exhibited deep modeling in their initial understanding of the challenge, shared problem frame, understanding feasibility, effective sub-divisions, shared mental models, approach to iteration, and how to prototype and test. However, despite a successful overall project, team members also highlighted struggles with initial understanding and inhibited shared mental models. This rich set of data allowed researchers to glimpse into a well-functioning, successful team to understand which deep modeling behaviors might be worth investigating further to help scaffold deep modeling for other university-industry collaborations or even for engineering students. Future work will investigate these productive behaviors to understand better how they counteract less productive (i.e., surface modeling) behaviors.

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