An Expert Solution to Assess an Industrially Situated, Computer-Enabled Design Project

Benjamin U. Sherrett,[a] Erick J. Nefcy,[a] Edith S. Gummer,[b] and Milo D. Koretsky[a]

[a]*Oregon State University,* [b]*WestEd*

Abstract

Background Process development is a common and critical task for industrial chemical engineers; however, it is difficult to create activities to give students such practice in their university education. Using a computer-based simulation, we have created an authentic, industrially situated process development task that students can complete by applying their foundational knowledge and skills. We present a case study of an expert's solution to this task, which is compared with those of higher- and lower-performing student teams.

Purpose The expert study sought to characterize modeling approaches to this task and to develop a set of target competencies to evaluate evidence of student learning as a guide to assessment.

Design/Method This comparative case study used ethnographic methodology to capture descriptions of the models and strategies that an expert and two advanced undergraduate student teams employed.

Results We categorized the expert solution into steps of information gathering, problem formulation, and iterative modeling and experimentation. We identified fourteen expert competencies and used them to assess two sample student solutions. Each student solution contained some expert competencies; a higher number of expert competencies are evident in the student team that had been previously identified as higher performing.

Conclusions The framework demonstrates constructive alignment of an authentic project task with evidence of student learning to evaluate the competencies students develop. This model example can be extended to other computer-enabled learning environments and, more generally, to capstone projects and other types of open-ended project work.

Keywords design education; interactive learning environments; modeling

Introduction

The potential for computers to positively impact educational practice is reflected in several recent studies characterizing student learning in computer-enabled learning environments (Quellmalz, Timms, & Schneider, 2009; Podolofsky, 2010; Clark, Nelson, Sengupta, & D'Angelo, 2009; Gredler, 2004; Vogel et al., 2006) and summarized in a recent National Research Council panel "Learning Science: Computer Games, Simulations, and Education" (Honey & Hilton, 2011). In this article, we investigate a learning system that places student

Journal of Engineering Education http://wileyonlinelibrary.com/journal/jee
October 2013, Vol. 102, No. 4, pp. 541–576 DOI 10.1002/jee.20027

teams in the role of real-world engineers to complete a complex task. The learning system is enabled by a three-dimensional computer simulation that provides the students with data representative of an authentic process. Other authors have referred to similar learning environments using terms such as "technology-enhanced student-centered learning environments" (Hannafin & Land, 1997), "computer simulations and games" (Honey & Hilton, 2011), and "computer enhanced learning environments" (Jacobson, 1991). In this article, we utilize the term *computer-enabled learning environment* as a general descriptor.

In the past decade, K–12 and university educators have devoted significant effort to developing and implementing computer-enabled learning environments; yet, systematic assessment practices have not kept pace with this rapid development (Honey & Hilton, 2011; Buckley, Gobert, Horwitz, & O'Dwyer, 2010; Quellmalz et al., 2009). In this article we describe an assessment framework we developed and used to investigate student learning in one such computer-enabled learning environment, the Virtual Chemical Vapor Deposition (VCVD) Learning System. The VCVD learning system is built on the situated perspective of learning (Johri & Olds, 2011; Collins, 2011). The learning system places students in the role of process development engineers working in teams to complete an industrially situated, authentic process development task. The experiments that student teams design are performed virtually using the computer simulation. Previous research in our group has demonstrated that while completing the process development task, student teams have opportunities to practice the complete, iterative cycle of experimental design in which they develop and refine solutions through experimentation, analysis, and iteration (Koretsky, Amatore, Barnes, & Kimura, 2008). Integral to their success is their ability to develop and operationalize models and to create appropriate strategies (Koretsky, Kelly, & Gummer, 2011a).

One challenge in assessing this complex, process development task is the broad spectrum of knowledge and skills that this activity elicits. While we acknowledge many other abilities are necessary to complete the task, our current focus is to specifically examine *modeling competencies* – the ability to apply knowledge and skill to develop and use models to complete the task. We use Schwarz et al.'s (2009) definition of a scientific model as "a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena" (p. 633). We extend this definition to the context of engineering by claiming that models allow engineers to better develop and evaluate possible solutions to a design task. Furthermore, we assert that a key element of engineering practice is the ability to apply and operationalize models.

Researchers have identified modeling as a critical element of engineering and science practice (Cardella, 2009; Gainsburg, 2006; Clement, 1989). Several innovative STEM learning systems, such as model-based learning (Buckley, 2000) and model-eliciting activities (Lesh & Doerr, 2003; Yildirim, Shuman, & Besterfield-Sacre, 2010; Diefes-Dux & Salim, 2009), have explicitly attempted to develop modeling skills in students. Theories regarding modeling in STEM fields contend that models are constructed from prior knowledge and newly gathered information and that they are refined in an iterative cycle of creation, use, evaluation, and revision (Buckley et al., 2010).

Figure 1, adapted from the work of Buckley et al. (2010), hypothesizes the iterative cycle of the modeling process as might be used by a student team in the VCVD process development task. The team first uses prior knowledge and information from the textbooks, journals, and Web sites to develop model components useful in understanding the system. The process of generating new model components may also involve the mathematization of concepts. Mathematization is

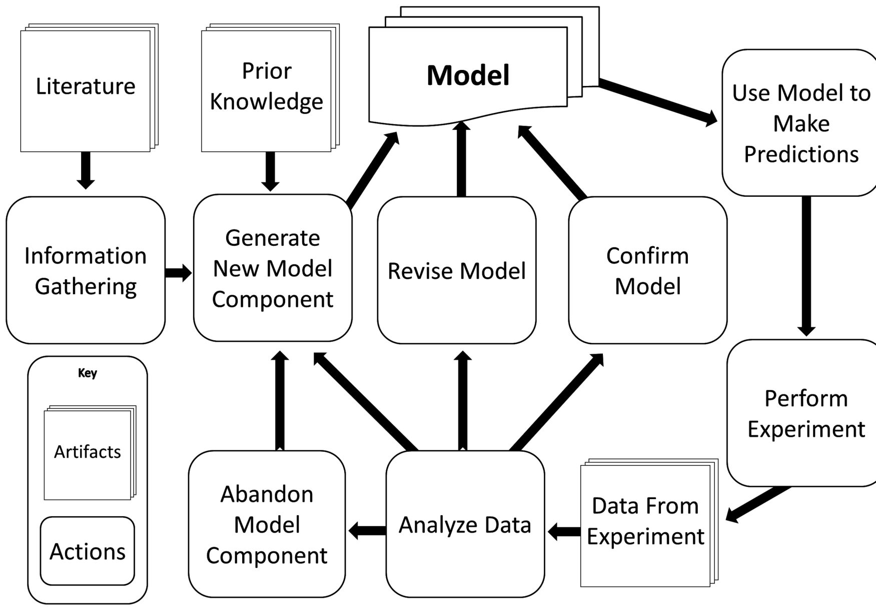

Figure 1 Diagram showing information gathering and the iterative cycle of model development, use, and refinement commonly implemented in experimentation in science and engineering.

the process of using mathematical constructs to afford greater understanding of real-world systems through activities ranging from "quantifying qualitative information, to dimensionalizing space and coordinatizing locations" (Lesh & Doerr, 2003, pp. 15–16).

These model components are then assimilated into an overall model of the system that is used to determine input parameters for an experiment. After running the experiment and collecting data, the team compares the data against their model, resulting in confirmation, revision, or abandonment of the model. Analysis of data may also lead to the development of a new model component. The team can then use the newly refined model to predict future runs. In this iterative process, the model informs input parameters, and data from the process performance informs modeling efforts.

This article explores the development and implementation of an assessment framework to determine the extent that student teams engage in modeling in the VCVD learning system. We base the elements of the framework on evidence centered design (Mislevy, Almond, & Lukas, 2003) and include the outcomes or competencies that are desired, the evidence that is obtained from student teams that demonstrate these competencies, and the task itself. The objective of this study is to characterize a set of competencies related to modeling through investigation of an expert engineer's solution to the VCVD process development task.

Our specific research questions are: What modeling competencies manifest as an expert completes the VCVD task? Do the competencies demonstrated by the expert inform the assessment of student learning as verified by the examination of student work? What are the implications of the findings of this study for research and practice of engineering education?

Learning and Assessment in Computer-enabled Learning Environments

Types of Computer-enabled Learning Environments

Computer-enabled learning environments have been created to address a wide range of content. STEM examples range from reinforcing conceptual understanding of core biology (Horwitz, Neumann, & Schwartz, 1996), chemistry (Tsovaltzi et al., 2010), and physics (Wieman, Adams, & Perkins, 2008) to understanding complex biological systems (Buckley et al., 2004).

Computer-enabled learning environments can also be examined regarding the role and context within which these environments intend to place students. From this perspective, two primary types of learning environments emerge. In the first, a student is placed in a typical classroom or teaching laboratory. In this role, the student performs tasks common in traditional classrooms or laboratories except that they are performed on a computer. Many virtual laboratories provide this type of environment. In the second type, the software and instructional design attempts to remove students from the role and context of a traditional classroom or laboratory and place them into another role and context. We term such cases *situated computer-enabled learning environments*. Examples include learning environments that place students in the role of a wolf hunting in the wilderness (Schaller, Goldman, Spickelmier, Allison-Bunnell, & Koepfler, 2009), a video gamer traversing a challenging obstacle (Davidson, 2009), or a pioneer navigating the perils of the Oregon Trail (Chiodo & Flaim, 1993).

This article focuses primarily on a particular branch of situated learning environments in which the student is placed in the role of practicing professional. We term this case *industrially situated*. To set the context for the study, we next review literature describing the development and assessment of computer-enabled learning environments that (1) place the student in the role of a traditional student and (2) place the student in the industrially situated role of practicing professional.

Computer-enabled learning environments placing the student in the role of traditional student A large body of work describes computer-enabled learning environments that place students in the role of a traditional student. A common form of this type of learning system is the virtual laboratory created to replicate the physical laboratory (Sehati, 2000; Shin, Yoon, Park, & Lee, 2000; Wiesner & Lan, 2004; Pyatt & Sims, 2007; Mosterman et al., 1994; Hodge, Hinton, & Lightner, 2001; Woodfield et al., 2005; Zacharia, 2007; Abdulwahed & Nagy, 2009; Kollöffel & de Jong, 2013). In this context, the computer can reduce the resources required or help students better prepare for the physical laboratory. To enhance learning, developers sometimes supplement virtual laboratories with visual cues or alternative representations not possible in physical laboratories (Wieman et al., 2008; Dorneich & Jones, 2001; van Joolingen & de Jong, 2003; Finkelstein et al., 2005; Corter et al., 2007).

When assessing student learning in such computer-enabled learning environments, the analogous physical learning environment supports the use of preexisting assessment tools. Systematic studies to assess and compare learning between the virtual and physical modes are often performed. When such learning is compared directly, equivalent and often greater learning occurs in the virtual mode (Wiesner & Lan, 2004; Pyatt & Sims, 2007; Zacharia, 2007; Finkelstein et al., 2005; Corter et al., 2007; Campbell, Bourne, Mosterman, & Broderson, 2002; Lindsay & Good, 2005; Vogel et al., 2006).

Computer-enabled learning environments placing the student in the role of practicing engineer Industrially situated, computer-enabled learning environments place students in the role of a practicing professional; in these environments, students complete tasks commonly found in the workplace by interacting with simulated systems and instruments representative of real, industrial-scale devices. Development of these situated learning environments is motivated by the widely accepted claim that mastery of technical content alone does not equip students for professional practice. Rather, students should also engage in learning activities that promote the development of knowledge and skills associated with the application of this technical content to solve real-world problems (Bransford, Brown, & Cocking, 2000, p. 77; Litzinger, Lattuca, Hadgraft, & Newstetter, 2011; Brown, Collins, & Duguid, 1989; Herrington & Oliver, 2000).

By means of tabulated data or mathematical simulation, computers can rapidly generate data representative of real-world systems. Such data enables students to complete tasks representative of those found in industry. For instance, a computer-enabled learning environment gives civil engineering students the task of testing the dynamic responses of multistory structures to earthquakes while providing them with realistic data (Sim, Spencer, & Lee, 2009). In chemical engineering, learning environments based on full-scale industrial processes of styrene-butadiene copolymerization and hydrogen liquefaction have been reported (Kuriyan, Muench, & Reklaitis, 2001; Jayakumar, Squires, Reklaitis, Andersen, & Dietrich, 1995). One capstone environmental engineering design project used a computer simulation to allow students to perform as field engineers at a virtual hazardous waste site (Harmon et al., 2002).

In addition to a realistic task, some industrially situated, computer-enabled learning environments seek to provide a social context representative of industry. In these learning environments, students interact with peers and the instructor(s) as they would with colleagues and project mentors. The social context is meant to encourage students to enter a "community of practice" (Lave & Wenger, 1991), where they begin to reframe their identity in order to think, act, and value as do practicing professionals in their field (Shaffer, 2005). For example, a suite of computer-enabled learning environments offering both an industrially situated task and social context have been developed and termed *epistemic games* (Shaffer, 2005). The games put students in the role of professionals who are engaged in tasks in journalism, urban planning, and engineering (Rupp, Gushta, Mislevy, & Shaffer, 2010). In one such epistemic game, *Nephrotex*, students act as new hires at a high-tech bioengineering firm (Chesler, D'Angelo, Arastoopour, & Shaffer, 2011). They interact with a computer simulation to design an optimal dialyzer for a hemodialysis machine. The computer provides both the platform for experimentation and interactive correspondence with simulated co-workers and a graduate student acting as project mentor. Chesler et al. (2011) describe the instructional goals of the epistemic games as ranging far beyond the conceptual understanding pursued in many learning environments. The expanded instructional goals include developing the skills, knowledge, identity, values, and epistemology that are common to the community of practice within which the students are participating (Rupp et al., 2010).

Studies of industrially situated, computer-enabled learning environments commonly describe how computers help to deliver an innovative instructional design. But studies that assess and evaluate student learning in these environments are far less common. One likely reason is the challenge inherent in assessing students' acquisition of the rich set of instructional objectives typically put forth in these leaning environments (e.g., thinking, valuing, and identifying as a member of a professional community as mentioned by Rupp et al., 2010). Assessment strategies must be developed that align with the specific instructional objectives, and several approaches have been reported.

Hmelo-Silver (2003) investigated cooperative construction of knowledge in a clinical trial design task that was presented to medical students by a computer simulation. She used a think-aloud protocol along with a fine- and coarse-grain discourse analyses to argue that the learning environment promoted a joint construction of knowledge. While protocol analysis offers detailed insight into the actions and cognition of study participants, it is time consuming and impractical for the routine assessment of a large number of student solutions to a complex task.

Chung, Harmon, and Baker (2001) studied student learning in the capstone environmental engineering learning system cited above (Harmon et al., 2002) using pre- and post-concept maps. They compared student concept maps to one(s) generated by an expert in the field and found that the students' concepts and connections between concepts became more aligned with the expert after the learning experience. But a pre- and post-test approach may misalign task and assessment in industrially situated learning systems. Such learning systems are typically designed to develop a student's knowledge and skill within an authentic context; pre- and post-tests are often given in a sequestered context removed from the authentic task.

Evidence-centered Design as an Assessment Framework

While the studies cited above show evidence of student learning in industrially situated, computer-enabled learning environments, several procedural challenges limit the systematic and widespread assessment of student performance and learning in such environments (Honey & Hilton, 2011; Buckley et al., 2010; Quellmalz et al., 2009; Gulikers, Bastiaens, & Kirschner, 2004). These challenges include capturing complex performances that depend heavily on the authentic context within which they are presented, capturing student performance in authentic ways during performance of the task rather than before and after, and assessing student performance related to application of knowledge and skills rather than solely possession of such competencies (i.e., doing versus knowing). Recently, researchers have addressed these challenges using the framework of evidence-centered design (ECD) (Bennett, Jenkins, Persky, & Weiss, 2003; Rupp et al., 2010; Quellmalz et al., 2009; Bauer, Williamson, Mislevy, & Behrens, 2003; Shute & Kim, 2011).

The ECD framework (Mislevy et al., 2003) is built on the logical argument posited by Backwards Design (Wiggins & McTighe, 2005; Pellegrino, Chudowsky, & Glaser, 2001); that is, in order to effectively design learning environments, education designers should first identify learning outcomes, then determine what student actions will provide evidence of achievement of those outcomes, and finally, develop learning activities that will elicit those student actions. ECD builds on this logical progression by linking observations of student performance on a task with the likelihood that a student has achieved a given learning outcome using statistical methods such as Bayesian or social network analysis.

In ECD, the three curricular design components referred to in the preceding paragraph are termed *models*.* When ECD is applied to computer-enabled learning environments, there is a typical progression in the development of the three ECD models, as illustrated in Figure 2a. First, the *competency* (or *student*) *model* is developed. The competency model lists desired knowledge, skills, or other attributes to be developed and subsequently assessed. These competencies may be identified by the instructor, by mandated learning standards (Mislevy et al., 2003), by a

*While the ECD framework uses the term *model* to describe its three curricular design components, this article also uses *model* to describe a representation created to afford greater understanding. When referring to ECD, *competency*, *evidence*, or *task* will always precede *model*. We will always use the full terms *competence model, evidence model*, or *task model*. All other instances of *model* refer to its more general description.

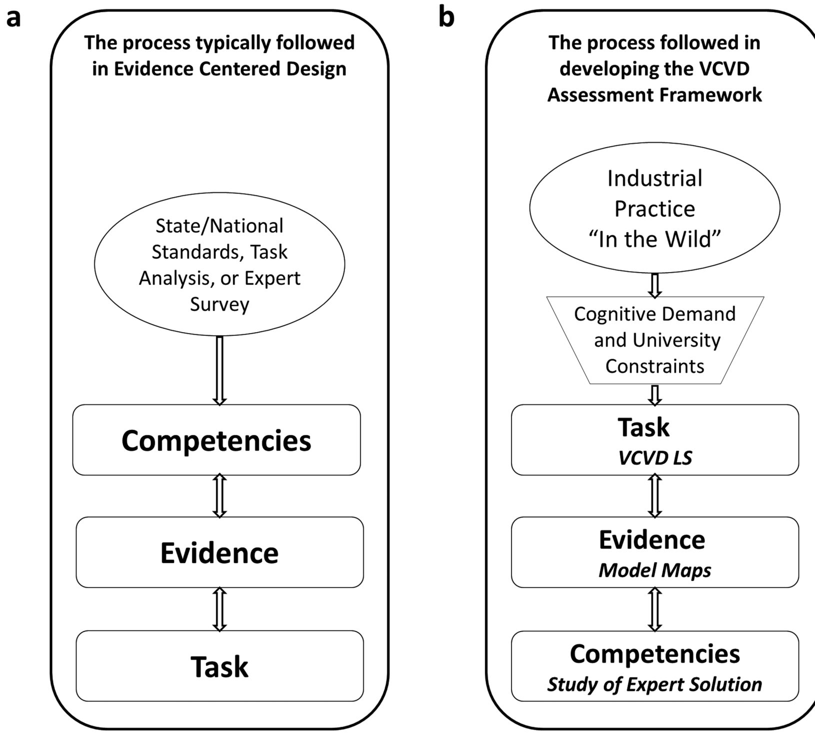

Figure 2 (a) The logical flow suggested by Backwards Design and ECD. (b) The flow of the assessment framework implemented on the VCVD learning system. The italicized texts show the artifact used to satisfy each of the three ECD models in the VCVD learning system framework.

task analysis of experts (Bauer et al., 2003), or by a survey of experts (Shute & Kim, 2011). Second, the *evidence model* is developed by asking what observable student response could provide proof that the student possesses the desired competencies. Third, the *task model* is developed by defining the specific tasks and actions that the students will be asked to complete in order to elicit responses that will in turn inform the evidence model.

The goal of our research is to be able to make trustworthy claims regarding students' demonstration of professional competencies required of chemical engineers. Our framework focuses on assessing the students' application of their knowledge and skills as they engage in an authentic engineering task, the VCVD process development task. To accomplish such an assessment, we focus on developing the three assessment models suggested by ECD. In developing the VCVD learning system, we have taken a fundamentally different approach from Backwards Design (Wiggins & McTighe, 2005) and ECD. We do not begin by defining a set of competencies to develop in students. Rather, we intentionally choose to first define an engineering task "in the wild" and then render it to the academic setting. This approach inverts the form of the ECD framework. In the following section, we elaborate on the justification for our approach and then describe the process of developing the three ECD models.

Development of the VCVD Learning System and Assessment Framework

We developed the VCVD learning system on the basis that thinking and learning are inextricably tied to the context of the given activity or task that prompts the thinking and learning (Bransford et al., 2000; Ambrose et al., 2010; Lave & Wenger, 1991; Shaffer, Squire, Halverson, & Gee, 2005; Litzinger et al., 2011; Johri & Olds, 2011). Our premise is that the cultivation of students' ability to apply their knowledge and skills in the wild is most effectively developed through engagement in tasks that reflect as closely as possible the authentic environments of professional practice (Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Prince & Felder, 2006; Bransford et al., 2000). Yet while providing an authentic context, we also must be mindful of the limits of students' cognitive resources and the other constraints of the academic environment.

With these ideas in mind, we focus first on an authentic task in the wild. Consequently, the ECD construct is inverted, as shown in Figure 2b. In the evolution of the VCVD learning system, the task model was developed first, based on characterization of typical tasks identified from interactions with practicing professional engineers in industry. Second, we developed the evidence model. As discussed above, development of modeling skills in students is a primary emphasis of the VCVD learning system. Thus, the evidence model must characterize the ability of students to develop models and identify strategies to employ these models to complete the task. Finally, this article describes the development of the competency model. Our framework relies on a task analysis of an expert engineer's solution to the same task that was given to students in the VCVD learning system.

Thus, instead of asking, "What competencies do we want students to demonstrate and how can we build a task that elicits those competencies?", we first ask, "What are elements of complex tasks that practicing engineers routinely perform?", and then, "Given an authentic task that embodies many of those elements, what competencies are necessary to engage in the task?"

While the task model and the evidence model are described briefly below, the framework for these models used in the VCVD learning system is based on more extensive work that is described elsewhere (Koretsky et al., 2008; Seniow, Nefcy, Kelly, & Koretsky, 2010; Koretsky et al., 2011a). This article identifies their role in an assessment framework that necessitates the development of the third component, the competency model. In order to develop the competency model, we examine the solution of an expert.

Task Model

The process of developing the task model began with informal interviews with engineers during industrial research projects, with student interns and their project supervisors, and with our school's Industrial Advisory Board. We then developed a list of common traits of complex engineering tasks. This list was confirmed by task characteristics of practicing engineers that are described in the literature (Herrington & Oliver, 2000; Todd, Sorenson, & Magleby, 1993). Such tasks

are commonly completed using an iterative cycles of design and analysis,

involve systems that function according to complex phenomena that are not easily understood and cannot be classified with absolute certainty due to variations in process and measurement,

are completed in a social context and typically involve interacting with teammates and a project supervisor or a customer, have ambiguous goals and competing performance metrics requiring engineers to make difficult decisions about trade-offs in performance in order to produce the "best" possible solution, and

are completed with an emphasis on budgetary and time constraints.

In designing the VCVD learning system, we chose a specific task from industry that aligns, as much as possible, with these general traits. Students are placed in teams and play the role of process development engineers. They are tasked with determining a recipe of input parameters for a chemical vapor deposition (CVD) reactor so that it can be released to high-volume manufacturing. Students evaluate their input parameters by designing and performing experiments and analyzing the results.

We also designed the task to be as authentic as possible within the constraints of a class setting. The student teams design and perform experiments virtually within a three-dimensional user interface intended to replicate a semiconductor processing facility. Data for students are generated from an advanced mathematical model of the process, and random and systematic process and measurement error are added to the output. Data are only provided for the process parameters the students choose to run at the wafer locations that they choose to measure. In analogy to industry, student teams are charged virtual money for each experimental run and each measurement. Research of students' perceptions has shown that students believe that the VCVD task is representative of a real-world engineering task (Koretsky, Kelly, & Gummer, 2011b).

"Good" runs are chosen according to a trade-off between two performance metrics, product quality (uniformity of the thin film deposited to a target thickness) and process efficiency (amount of chemicals used and time of process). Additionally, the student teams seek to complete the task while keeping their total experimental costs as low as possible. Optimizing performance in one metric typically results in decreasing performance in the other metric; this trade-off requires student teams to evaluate the relative importance of both performance metrics and their total experimental cost. Due to the complex interactions between input parameters and performance metrics, an iterative problem-solving approach is necessary. Since the data are collected easily through the computer, student teams are afforded opportunities to practice the complete, iterative cycle of experimental design within the time frame and resources available to an undergraduate course (Koretsky et al., 2008; Koretsky, Barnes, Amatore, & Kimura, 2006).

While we report the assessment framework for this specific task for chemical engineering, the list of traits associated with authentic engineering tasks is general, and this approach could be used in a similar way to identify and develop authentic tasks for a wide variety of engineering disciplines.

Evidence Model

One central desired outcome of the VCVD learning system is to have student teams engage in modeling to help them complete the experimental design task, so they can recognize and use their engineering science background to more effectively pursue the experimental design process, rather than being explicitly instructed to use a specific model. Through our experiences with this learning system, we have observed a wide spectrum of model components that students have developed in their efforts to complete the task. These components include quantitative predictive analytical model components, qualitative descriptive conceptual model components, and empirically based statistical model components. There is also a range of sophistication in both the model components themselves and the ways in which the students operationalize them to complete the task.

In order to capture evidence of the modeling activity student teams demonstrate, we have developed an analysis framework called Model Development and Usage Representations, or, in short, Model Maps (Seniow et al., 2010). Model maps provide a succinct and graphical representation and are used as the evidence model in our framework. The model maps analysis technique looks in vivo at the solution path followed by student teams, focusing on the model components that they develop and how they use their model to complete the VCVD task. The construction of a model map involves transforming information from student work products into an information-rich, chronological representation of the solution path that was followed. In this way, a team's solution to the VCVD task, which typically takes a team of two to four students 10 to 60 hours to complete, is reduced to a one-page graphical representation. This condensed representation reduces the time required to evaluate the modeling competencies of many teams and enables direct comparisons between the teams.

The model maps analysis framework graphically displays information regarding a student team's model components and experimental runs by associating characteristics with specific symbols. Figure 3 gives the symbols and their descriptions. Model components are represented according to their type (qualitative or quantitative) and their action (operationalized, abandoned, or not engaged). Additionally, the impact of modeling activity for each experimental run is identified by the shape associated with the run-type markers. Finally, additional descriptors further describe the modeling process, such as identifying components that are clearly incorrect or sources used in information gathering. All of these features are organized along a line representing the chronological progress of the team's solution path.

Model maps are constructed by researchers based primarily on interpretation of information contained in the experimental design notebooks that students are required to keep. While notebooks have been a primary source of data in other studies aiming to characterize student cognition in engineering design problems (Sobek, 2002; Ekwaro-Osire & Orono, 2007), we acknowledge they are limited by the varying degree to which participants record their cognitive processes and our researchers' ability to correctly identify and interpret the intended meaning of the student inscriptions.

To address these issues, we take two approaches. First, students are explicitly requested to keep detailed notebooks describing the experimental design that they execute and justifying the reasoning behind strategic decisions. The teams participating in this study complete a physical laboratory project immediately before the VCVD process development task. During the physical laboratory, they have been instructed and provided feedback on keeping detailed notebooks. The notebooks in both the physical laboratory and the VCVD task are graded on the basis of their content and level of detail. Second, the model maps coding process relies on additional sources of data: the database of student run and measurement parameters cataloged by the VCVD computer program, the memoranda that teams are required to bring to the design strategy and project update meetings, and the team's final report and oral presentation slide show. The information from these sources serves to confirm, explain, or expand upon the notebook content.

The construction of model maps is based on a reliable and valid coding method that is described in greater detail in Seniow et al. (2010). Recently, our group has compared model maps constructed using the methods described in this study (coarse-grain size) to model maps constructed using transcripts from audio recordings of teams throughout their work on the VCVD task (fine-grain size). We have found that while model maps constructed on the basis of the finer-grain approach provide greater detail, the fundamental characteristics of the solution path are well represented by the model maps technique used in this study (Nefcy, Gummer & Koretsky, 2012).

	Symbol	Name and Description
Type of Model Component		Circles represent **qualitative model components**; relationships that do not rely on numbers, e.g. *"As pressure decreases, uniformity increases"*
		Rectangles represent **quantitative model components**; relationships that rely on numbers (typically in the form of equations), e.g. *"Film Deposition Rate=Reaction Rate Constant x Concentration of Reactant"*
Modeling Actions		An **operationalized model component** is one that is developed and then used throughout the solution process.
		Abandoned model components are developed and then clearly abandoned.
		A model component is classified as **Not Engaged** if it is clearly displayed in the notebook but no evidence exists of its use.
Run Type		A quantitative model is used by the group to determine the parameter values for **model directed runs**.
		A statistical approach is used to determine the parameter values for **statistically defined runs** (e.g. DOE)
		Teams analyze the data provided by **qualitative verification runs** to qualitatively verify models that they have developed.
		No explicit reason is given or deducible for **runs not explicitly related to modeling**. Often they represent a "guess and check" or a "fine tuning" run.
Additional Descriptors		An X is placed over any **clearly incorrect model component**.
	Problem Scoping Sources	A box is shown at the beginning of the map, signifying the **Information Gathering** stage. All sources listed in notebook are displayed.
	Model	**Primary model components** are along the central problem line and are used repeatedly and are essential to the overall solution.
	Model	**Secondary model components** are connected to the central problem line and are peripheral to the overall solution
	Material Balance \#	A **run reference number** denotes the run(s) which a given model component was explicitly applied.

Figure 3 Legend giving the meaning of the symbols used in the model maps analysis technique.

Competency Model

In this study, we seek to develop an appropriate competency model based on the task model and the evidence model described above. To achieve this objective, we observed an expert chemical engineer's performance while he completed the VCVD task and characterized his solution using model maps. This approach derives from studies of expertise in the learning sciences (Bransford et al., 2000; Litzinger et al., 2011; Atman, Kilgore, & McKenna, 2008) and is intended to capture the modeling competencies. Once developed, the competency model may be used together with the evidence model (model maps) to assess student solutions to the VCVD task.

As mentioned above, our work is focused on characterizing expert competencies associated with modeling. To frame our investigation of the expert's solution, we focus on three fundamental stages of the modeling process as discussed in literature (Buckley et al., 2010) and as interpreted in the context of modeling in the VCVD learning system in Figure 1. We define each of the stages below and discuss prior findings from literature.

Information gathering As shown in Figure 1, information gathering provides a primary way to initiate the modeling process. It has previously been identified as a competency critical to modeling (Maaß, 2006). Correspondingly, information gathering is a common focal point in many studies of expert solutions to problems in a variety of fields (Robinson, 2011; Delzell, Chumley, Webb, Chakrabarti, & Relan, 2009; Kirschenbaum, 1992). Studies in engineering education have focused on information gathering in the context of design problems and have found that experts exhibit significantly different patterns in information gathering than do students. Atman et al. (2007) found that experts spent more time gathering information, requested information more often, and requested information from more categories than did students. These findings are consistent with other studies in engineering that have identified information gathering as a critical stage in the design process (Jain & Sobek, 2006; Ennis & Gyeszly, 1991).

Formulating the problem As shown in Figure 1, model components are generated before the first experiment on the basis of gathered information and prior knowledge. These initial model components are generated so that the problem solver may understand the problem and frame it so that action (in this case, performing experimental runs of the virtual reactor) may ensue. Such activity is referred to as problem scoping, problem structuring, or problem framing. Studies of engineering designers have shown that such activity is an important stage in design (Restrepo & Christiaans, 2004), albeit one that varies on the basis of context of the problem and the designer's past experience (Cross & Cross, 1998; Cross, 2003).

Iterative modeling and experimentation Iteration of modeling and experimentation is shown in Figure 1 as the clockwise arrows, which denote the cyclic progression of the solution path. The process involves using a model to determine the input parameters for an experiment and then revising that model on the basis of the analysis of the experimental results. Iterative modeling not only is beneficial in the development of conceptual understanding in the modeler (Lesh & Harel, 2003) but also is considered an essential ability of scientists (Buckley et al., 2010). Iteration is also commonly considered a critical aspect of the engineering design process (Ullman, 2009). Adams (2001) showed that in the context of engineering, iterative design practices vary on the basis of experience and correlate with success in design projects.

Research Design

This study is part of a larger research project that seeks to understand how engaging engineering students in computer-enabled, authentic engineering tasks enables the development of their engineering skills. The overall project is based on a theoretical framework of design research in education. In design research, multiple theories contribute to the development of working hypotheses or conjectures that are then iteratively examined from multiple perspectives (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Lesh, Kelly, & Yoon, 2008). In the present comparative case study, we seek to capture descriptions of the models and strategies employed by an expert and by higher- and lower-performing advanced undergraduate student teams. Ethnographic methodology is best suited for this type of data gathering and analysis. By gathering rich observational data as the expert and the student teams complete a complex engineering task and supplementing this observation with work artifacts and interview data, we generate thick descriptions of the approaches adopted by the participants (Geertz, 1973). We then use a detailed and systematic coding scheme to develop graphical, information-rich representations of the solution path that they followed (Miles & Huberman, 1994). We interpret the representations together with the participants' work artifacts to form a composite of competencies they used. Finally, we compare the cases to typify the distinctive attributes of the models, strategies, and reasoning used by the expert and student teams (Ragin, 1987). The goal is not to provide the single definitive set of competencies that are needed to complete the task, but rather to portray a range of responses and to distinguish similarities and differences among participants.

Participants

The expert in the study is a highly qualified chemical engineer, who received his undergraduate and doctorate degrees in chemical engineering from top-tier programs and has 18 years of industrial experience in both high-tech and pulp and paper industries. His industry positions have included roles in microfluidic design, mechanical design, reaction engineering, and research and development management. He has been promoted regularly and obtained a management position and a designation of "master engineer" in a global high-tech company. The expert holds over 20 patents and is generally acknowledged by his peers for his technical mastery.

The expert, though, did not have any specific experience working with CVD processes. This choice was deliberate because we wanted an expert who would need to activate his foundational domain knowledge to complete the task and not rely on any specific practical experience from similar tasks, as is the case in other reported studies (Johnson, 1988; Hmelo-Silver, Nagarajan & Day, 2002). The lack of process specific experience aligns his approach with that of the students; both must complete the task by activating their foundational domain knowledge.

One limitation of the study is that the expert worked alone. We believe this put the expert at a disadvantage since he did not have the rich sociocultural environment experienced by students. Our results should be considered with this difference in mind. In the future, we intend to study teams of experts so that we can further discern important sociocultural elements in the solution process.

The two student teams, each of three members, were selected from senior chemical, biological, and environmental engineering students at Oregon State University. The teams were chosen on the basis of an independent, holistic assessment of 15 teams and were identified by the course instructor as representing typical low- and high-performing teams. The selection and discussion of student solutions perceived as representative of the general student population has been used in other studies of problem solving in engineering (Atman, Bursic, & Lozito, 1996).

The students were assigned the VCVD process development task as one of three laboratory projects in the first quarter of the senior capstone laboratory sequence. Prior to this course, students had completed courses addressing core chemical engineering science content such as material balances, reaction kinetics, mass transfer, and statistical analysis of data including design of experiments (DOE). Students self-selected into teams in their laboratory sections.

For this study, the first author, a graduate student in mechanical engineering, analyzed the progress towards expertise in design. The second author, a graduate student in chemical engineering, helped develop the model maps analysis technique and contributed to the analysis of models and model components. The third author provided expertise in research methodology. The last author developed the learning system and directs a research program to characterize the ways these types of system influence student engagement and learning. The project was approved by the Institutional Review Board and all participants signed informed consent forms.

Task

Both the expert and students performed the same VCVD learning system process development task and were given three weeks to complete the project. All the participants were first given an introductory presentation containing background information regarding thin films manufacturing, the CVD process, and the basic principles contributing to CVD.

During the project, the expert and the students were required to meet with the faculty member serving as project supervisor twice. In the first of these project update meetings, the participants were asked to present their experimental strategy, including their proposed first experimental run parameters and overall projected budget. In the second meeting, the participants updated the project supervisor about their progress and outlined the experimental strategy for completing the task. In both meetings, the faculty member intentionally tries to maintain the situated environment for the project. Students were required to bring typed memoranda to each meeting, while the expert was asked to verbally describe the items listed above.

All participants performed all experiments using the VCVD reactor and used the user-interface to submit their final recipes of input parameters. After submitting a final recipe, the students were required to deliver final oral and written reports, whereas the expert was not. These activities develop communication skills and promote reflection and metacognition. However, the activities would have minimal impact on our analysis of the expert modeling competencies, and we simply could not ask the expert to spend the time required to prepare the reports.

Data Sources

We used five data sources for this study. Evidence from the multiple data sources allows triangulation and investigation of alternative explanations to ensure trustworthiness. First, participants were instructed to thoroughly document their work in a notebook. They were instructed to keep track of the run parameters, output, and data analysis, and to explain what they inferred from the analysis and what they planned to do next. After the project, the notebook was collected for analysis. Second, experimental information was gathered from the VCVD computer program. This source provides the parameter values participants used in all experiments and their reported results. Third, for the students only, work products were collected including the two typed memoranda and their final written report and final presentation slides. Fourth, the expert was audio recorded as he verbalized his thought process as he solved the problem. All audio recordings were then transcribed. Fifth, the first author interviewed the expert after the project using a semistructured format with both open-ended and directed questions. The interview was audio recorded and transcribed. We used the interview as a member check on our interpretation from the other sources.

Analysis Methods

The study's primary analysis method was the development and interpretation of model maps for each participant, as described in the Evidence Model section above. As mentioned, the notebook, additional work products, and experimental run data from the VCVD computer program are the data sources we used to construct model maps. We performed further analysis using model maps in two stages to address each of the first two research questions.

We addressed the first research question regarding the expert's modeling competencies by interpreting the information in his model map in the context of commonly identified features of expertise and commonly accepted expert practices in modeling. The map interpretation provides evidence about the manifestation of such expert traits during the VCVD process development task. To gain greater insight into the expert's modeling activity, traits identified in the expert model map were investigated further by searching the project and interview transcripts, and revisiting the expert's notebook. In this fine-grain analysis, transcripts and the notebook were reviewed in their entirety, and the first author parsed out segments of these documents that were related to the traits identified in the analysis of the model map. In the case of longer sections of parsed data, we interpreted the statement and present a discussion of our interpretation. In cases of shorter and more direct parsed segments, the data is presented directly along with a discussion.

To address the second research question, we analyzed model maps for the two student teams. This analysis examined the model maps from both teams for the expert modeling competencies previously identified.

For the third research question, we interpreted the findings in the context of our classroom and curricular experiences and in the context of the engineering education and cognitive science literature.

Results

This section presents the expert's solution as represented by a model map and includes the identification and discussion of the modeling competencies demonstrated in the three stages of his solution. We then assess the solution of the student teams on the basis of the expert's competencies.

The Expert's Solution

The model map developed from analysis of the expert's work products is shown in Figure 4. The model map depicts activity in chronological order by reading clockwise from the upper left. It can be interpreted using the three stages of modeling. The expert began the solution to the VCVD task with information gathering and cited six sources. The expert then developed 11 model components in formulating the problem. These model components appear before the first experimental run (the small, solid black square run marker labeled "1"). Next, he entered the solution stage of iterative modeling and experimentation. In this stage, he used information from eight experimental runs to revise two of his previously developed model components and develop three new model components. The expert concluded his solution by submitting a final recipe of inputs (Final Parameters) for release to high-volume manufacturing. We next identify the competencies that are demonstrated by the model map associated with each of the three stages.

Information gathering The information gathering stage typically involves searching texts, journal articles, and Web sites. The model map (Figure 4) of the expert's solution indicates that six references were listed in his notebook. Three of these sources were engineering texts, two were journal articles, and one was a Web site. Direct examination of the expert's notebook yielded insight into the competencies demonstrated during this stage of his solution. For example, in identifying the input parameter values reported in one journal article

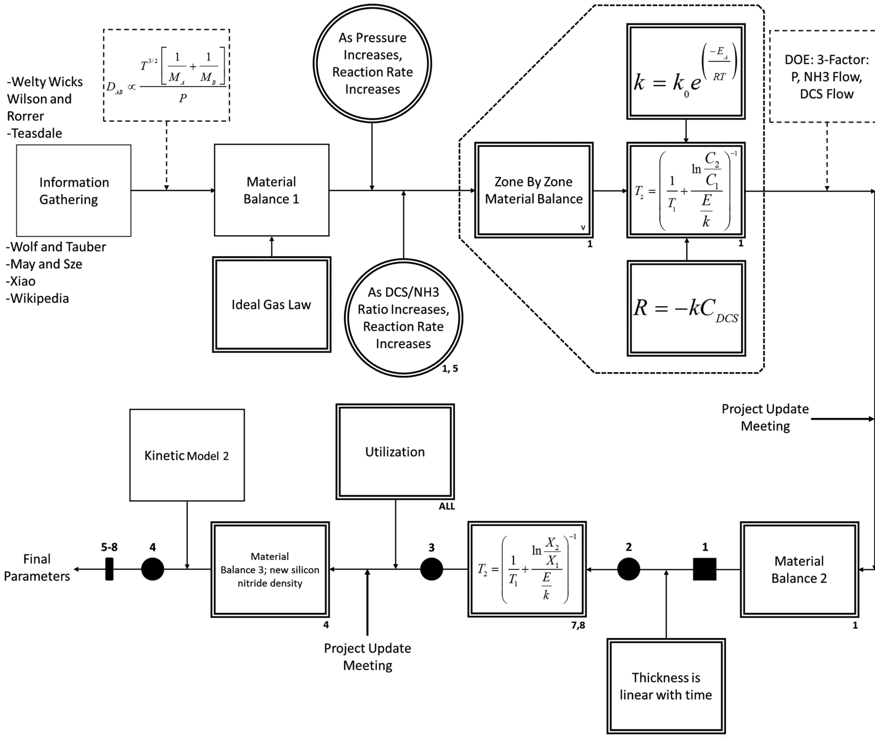

Figure 4 Model map displaying the information gathering and modeling demonstrated by the expert in his solution process. The dashed hexagon is included to illustrate the four interlocking model components that form the core of the model.

("Teasdale" in the Information Gathering box; see Teasdale et al., 2001, in Reference list), he noted that the reactor volume reported differed from the reactor for which he was developing input parameters. We interpret this note as a reminder not to blindly input all parameters found directly to the VCVD process. In citing the range of input parameters from the Wolf and Tauber (1986) text, he noted one of the essential constraints limiting the maximum temperature in CVD processes, i.e., the typical range of temperature that the reactor can operate in before it transitions into a regime wherein product uniformity dramatically decreases. This transition point in CVD reactors became a focal point in the expert's efforts later in formulating the problem.

Using Wolf and Tauber (1986), the expert also noted the qualitative effect that the input parameters of pressure and flow ratios of the two reactants have on the deposition rate of the film. Figure 5a shows the expert's notes regarding this relationship. Examination of the expert's model map shows that this information was later assimilated and became two qualitative model components (indicated by being outlined by the double circles in Figure 4), which were useful in formulating the problem and performing iterative experimentation and modeling (used to determine input parameters for Runs 1 and 5). The expert's information gathering continued in this pattern; he cited sources and extracted material that he identified as useful. To make

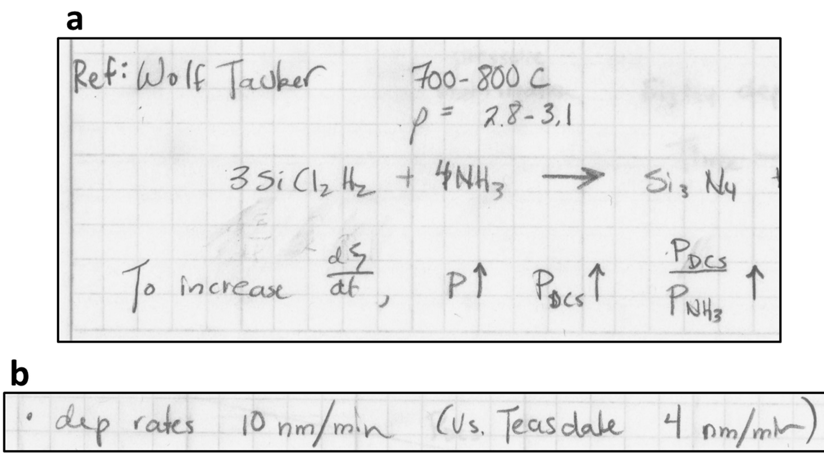

Figure 5 Two excerpts from the expert's notebook showing (a) the formulation of a qualitative model component relating deposition rate ($\frac{d\zeta}{d}$) to pressure (P) and input flow ratios ($\frac{P_{DCS}}{P_{NH_3}}$) and (b) an explicit comparison between deposition rates (dep rates) found in two literature sources.

judgments regarding the validity and applicability of the information he found, he compared inputs and relationships reported in various sources to one another and to the process on which he was to perform experiments. A sample of this activity is found in Figure 5b. In this example, the expert explicitly compares a deposition rate reported in Wolf and Tauber (1986) to a deposition rate reported in Teasdale et al. (2001).

In summary, the expert's information gathering activity demonstrated the following competencies: collection of multiple (six) sources from texts, journals, and the Internet; evaluation of information credibility and applicability by cross referencing sources and comparison of reported systems to the system being optimized; and assimilation of information thought to be reliable and applicable to form the foundation for model development in future solution stages.

Formulating the problem In the expert's model map (Figure 4), evidence of modeling activity in the problem formulation stage is shown between the Information Gathering box and the first experimental run, indicated by the solid black square run-type marker labeled "1." During problem formulation, the expert placed an emphasis on modeling, developing 11 of the 16 total model components represented on the model map. Furthermore, 10 of the 11 model components are based directly on his fundamental knowledge of chemical engineering first principles (all but the "DOE: 3-Factor" in the dashed box). Finally, the core of his modeling activity is represented by four clustered model components. These components are indicated by the added dashed hexagon in the model map. We term them *clustered* since they are integrated and become applied as a whole.

The modeling activity in the problem formulation stage culminates in a first experiment, which we term *model directed*, as indicated by the solid black square run-type marker. In a model directed run, the model is used to predict exact numerical values for the input parameters for the experimental run. Such behavior is aligned with the overall goal of the VCVD learning system: to develop in students the ability to apply fundamental chemical engineering principles to solve real-world engineering problems. The project supervisor has witnessed student teams performing similar model directed runs; however, in experience with over 100 teams, he has never observed a student team use modeling to determine their *first* experimental run parameters. We argue below that the expert's performance in this regard indicates sophisticated modeling ability that is facilitated by a broad set of competencies.

Key to the expert's modeling strategy is the identification of a critical element to the reactor performance that focuses and directs his modeling activity. Identification is followed by conceptualization, mathematization, simplification, and solution. We base interpretation on evidence in the expert's design notebook and the audio recordings of his project work, and it is confirmed through the post-project interview. Below we elaborate on this sequence of observed modeling activity.

To understand the expert's modeling approach, some engineering science background is needed. CVD reactors can be operated in two regimes, mass-transport limited and reaction-rate limited. The input parameters determine the regime in which the VCVD reactor operates. However, the different zones along the reactor may operate in different regimes since the conditions change as the feed gases react to form products (the film and waste gases). The operating regime is critical since one regime enables high film uniformity (one of the quality metrics) and the other does not. However, the desired regime also results in slower film growth rates and correspondingly longer process times (a cost metric), which is not desirable. As a result, a good solution strategy is to find the transition from one regime to the other and to select input parameters so that all of the zones operate just barely within the desired regime. This strategy results in a film that is grown as fast as possible but is still uniform.

In the process of formulating the problem, the expert first determined that reactor regime is critical to performance. This determination was based on a combination of information gathered and his understanding of first principles. Next, through a qualitative conceptualization of the processes occurring along the length of the reactor, the expert correctly recognized that the last zone of the reactor is most susceptible to transition to the undesired regime. The audio transcripts from the project work provide direct evidence of this conceptualization. However, due to the technical nature of the utterances, we omit them from this article.

The expert's notebook reveals that he mathematized his conceptual understandings by generating a set of four interconnected, quantitative model components based on first principles. These model components were identified using model maps analysis and are shown in Figure 4 in the dashed hexagon. He used this quantitative model along with the needed conditions at the last zone of the reactor to determine what conditions were required in each of the prior zones. In other words, the expert developed his model in a backwards manner, starting with the conditions needed at the critical last zone of the reactor and then modeling each zone forward to determine input parameters to the first zone.

In solving equations to determine numerical values, the expert purposefully simplified some of the quantitative model components. That is, the expert's notebook shows quantitative model components of greater complexity than those he ultimately used to determine input parameters. Although the expert did not directly state why he chose to use the simplified model components, he was readily able to apply the simplified model components and achieved values for the input parameters to his first experiment. The more complex model components may represent an alternate approach to be used by the expert if the simplified modeling approach proved insufficient. Such actions of developing, simplifying, and solving mathematical equations to model a real-world system demonstrate a high level of mathematical procedural competence.

The interconnected nature of the expert's modeling activity, particularly those model components shown in the dashed hexagon in Figure 4, suggests that the expert's conceptual knowledge was well organized and he accessed it in a coherent manner. These model components were written in his notebook in a sequential and integrated manner and were holistically and successfully employed to determine input parameters. Such well-connected bodies of knowledge (commonly referred to as *schemas*) are often considered to afford more efficient access and correct application of knowledge when solving a problem; experts are typically acknowledged as having more developed schemas than novices (Bransford et al., 2000).

Further evidence of the expert's advanced knowledge access and application is found in two previously mentioned features of his solution. First, to develop his model in a backwards manner, the expert needed to conceptually characterize the reactor behavior – both to identify the desirable regime and then to determine which end of the reactor was most susceptible to transition out of this regime. The expert would not have been capable of employing this strategy if he considered fundamental principles in a piecemeal fashion. Rather, this conceptualization required the expert to simultaneously apply multiple fundamental chemical engineering concepts. Second, in formulating the quantitative model, the expert again demonstrated his interconnected knowledge structure; he mathematized his conceptual understanding of how the reactor worked through complementary equations, such that all equations could be solved simultaneously.

Analysis of the expert's post-project interview provides evidence of the intentionality of his model-intensive approach in problem formulation. When asked simply to reflect on the project, the expert mentioned his focus on the initial part of the solution several times. He discussed the effort he spent learning about the mechanisms that affect CVD, "I really wanted to understand what I was trying to do before I started." Later in the interview, he articulated two reasons for this emphasis, both situated in his industrial experience. He first mentioned a focus on understanding the problem: "As a seasoned professional, if I don't understand my objectives, I can't make good engineering decisions." He also mentioned his desire to maintain his credibility in industry: "You got to have your ducks in a row before you walk up to someone [an operator or supervisor] because that first impression of credibility is really important." The expert then mentioned the role of understanding and application of chemical engineering principles in formulating the problem, "What you don't want to do is go up to equipment and start running things, building things and not think about the basic principles at play." He continued to state, "I believe in the application of our [chemical engineers'] training in scientific fundamentals to solve problems" and "So you look at something [referring to a new project] and you immediately go to the physical principles that you were trained in and begin to apply them."

In summary, while formulating the problem, the expert demonstrated the following competencies: he identified that operating regime was a critical feature of the problem; he conceptualized the reactor's operation to identify where and how the operating regime issue would manifest in the reactor; he transferred his conceptual understanding of how the reactor worked into a series of mathematical equations; he chose to simplify the mathematical model components, which he then solved to determine input parameters; and strategically, he placed a distinct emphasis on modeling to understand the problem before performing experiments.

Iterative modeling and experimentation to solve the problem During the iterative modeling and experimentation stage, the expert iteratively used his model to predict experimental input parameters. He also revised his model on the basis of analysis of experimental results and on discussions with the project supervisor during project update meetings. His first experimental run's input parameters were determined on the basis of his quantitative modeling. Additionally, model maps analysis reveals that, of the eight experimental runs performed by the expert, explicit evidence of the application of model to determine input parameters existed in all but two runs (Runs 3 and 6). Regarding the revision of his model, although the majority of the expert's model components were developed before his first experimental run, he generated five model components while performing experiments, three of which were explicit revisions of earlier model components (Material Balance 2, Kinetic Model 2, and T_2=…).

We gained further insight into the iterative nature of the expert's modeling and experimentation and of his metacognition regarding strategy through analysis of his notebook. Figure 6 shows two excerpts from the expert's notebook that explicitly demonstrated his iterative plan of modeling and experimentation. In Figure 6a, the expert has defined his first experimental run input parameters and is describing his future plans after performing the first experiment and analyzing the data. The cyclical diagram shows that after running his first experiment, he plans to verify the "coherence" of his theory. If the theory is found coherent, he will transition to experiments guided by a factorial experimental design, a commonly used experimental design from the design of experiments (DOE) methodology. DOE lays out patterns for determining experimental inputs so that empirical data may be gathered and analyzed using statistical principles to develop empirical, quantitative models predicting the relationship between inputs and process performance. If the expert's theory is not coherent, he will modify his theory and run another experiment. Evidence from transcripts of audio recordings revealed that this plan was further iterated upon because the expert did verify his theory, but chose to apply a tuning process guided by first principles knowledge instead of a factorial experimental design.

Figure 6b is a similar diagram from the expert's notebook, which he inscribed after his fourth experimental run. In this diagram, the expert shows his solution path forward after analyzing Run 4. The notebook excerpt reveals that if the characteristic shape of film deposition is

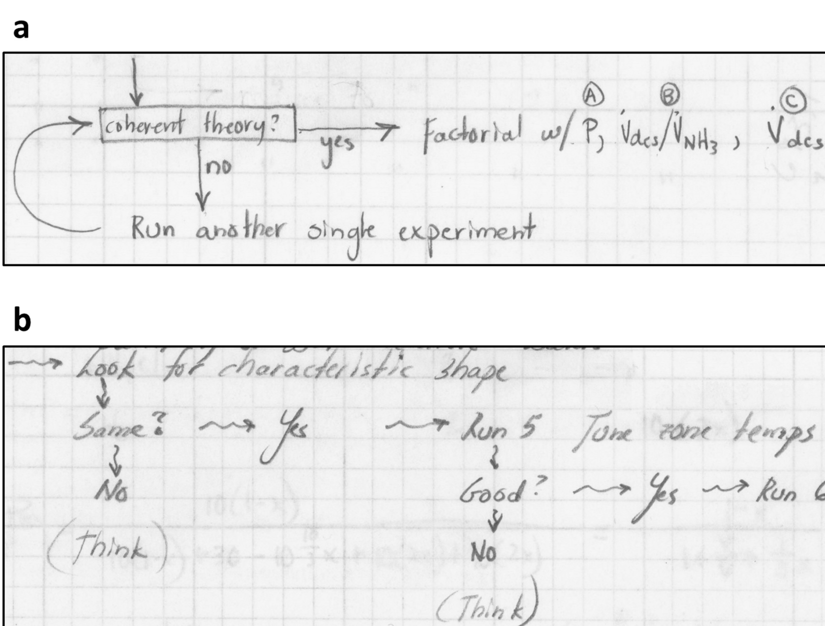

Figure 6 Two excerpts from the expert's notebook describing his iterative approach to modeling in his solution to the VCVD task.

the same (signifying good film uniformity), he will proceed to perform Experiment 5. If not, he will think. A similar reactive process is proposed to follow Run 5. The audio transcript reveals evidence of the expert's thinking regarding the factors contributing to his future strategic choice – specifically, whether to apply qualitative modeling to increase flow rates or to move back towards a more first-principles quantitative approach of tuning temperature zones. This reasoning is evident in the following except:

> So it is interesting. I need to start thinking about what I am going to do depending on what these results look like. If I bring up that curve, it is still monotonic, but if I start to bring it up, then I'm going to go back in and bump the DCS flow up. If I go back to my concave up curve, I think that I will go to a temperature modification strategy.

The expert model map and audio transcript give additional proof of dynamic interaction between his solution approach and the feedback he received from analyzing experimental results. As mentioned in the formulating the problem stage above, the expert began the solution process implementing a quantitative first-principles modeling approach. However, in the middle portion of the solution process, he transitioned to an approach more reliant on qualitative modeling (used in Runs 2–6) and finally to a fine-tuning approach (Runs 7–8). During Runs 2–6, the expert adjusted parameters using primarily qualitative model components based on first principles, such as "As DCS/NH_3 Ratio Increases, Reaction Rate Increases." During the tuning runs, the expert used primarily a quantitative model component (the model component in Figure 4 denoted by the run numbers "7,8" below the box) to determine input parameters based on empirical data from analyzing past runs. Inspection of the audio transcript gave insight into why the expert considered alternative strategies:

> I think you have to wait and see how much change there is along the length and within the zones [referring to uniformity of the film thickness] to decide if I am ready to start my zonal temperature tuning, which I have always imagined is like the tuning variable.

This quotation and further examination of the corresponding text suggests that the expert attempted to level any monotonic increasing or decreasing of deposition along the length of the reactor using qualitative model components. His strategy then transitioned to using first principles to quantitatively tune the zonal temperatures. This tuning strategy resulted in the expert arriving at a recipe of inputs that he submitted as his final parameters.

The expert summarized the iterative nature of his solution approach in one of the last comments captured in the audio transcript. After completing his eighth and final experiment and selecting his final recipe of input parameters for submission to high-volume manufacturing, the expert reflected on the solution process: "Pretty happy with that result and I am going to stop there. Kind of neat to see how [my solution process] iterated to the answer."

In summary, the expert's activity during this stage of the solution demonstrated the following competencies: the use of modeling to determine experimental input parameters and to converge on high-performing input parameters, the iterative evaluation and revision of his overall model, the use of first principles throughout the solution process, and the strategic transition between three different approaches for determining input parameters.

Summary of the expert's solution A summary of the modeling competencies the expert demonstrated in his solution to the VCVD task is shown in Table 1. The competencies represent our efforts to address our first research question: What modeling competencies manifest as an expert completes the VCVD task? They also constitute a preliminary competency

Table 1 Competencies Demonstrated in the Expert's Solution

Solution stage	Modeling competency demonstrated	Evidence from expert's solution
Information gathering		
	1. Identification of multiple sources of information from texts, journals, and the Internet.	Six sources cited including three chemical engineering texts, two journal articles, and one *Web site*.[a,b]
	2. Evaluation of information credibility and applicability through cross referencing sources and comparison of reported systems to system being optimized.	Explicit comparison among sources and between sources and the VCVD process.[b]
	3. Assimilation of information to form foundation for future model development.	Themes identified in information gathering developed into model components in later solution stages.[b,c]
Formulation of the problem		
	4. Identification of a critical aspect of the problem (reaction regime).	Identification of operating regime as critical to reactor performance.[b,c]
	5. Conceptualization of the reactor's operation.	Verbalization of relevant principles at play as the reaction occurs along the VCVD reactor.[c] Generation of multiple interconnected model components.[a,b,c]
	6. Mathematization of conceptual understanding. 7. Simplification of mathematical equations. 8. Solution of mathematical equations.	Generation and solution of simplified mathematical equations predicting reactor performance.[a,b,c]
	9. Strategic emphasis on modeling before experimentation.	Eleven model components developed before the first run.[a,b] Discussion of importance of understanding applicable first principles before experimentation.[d]
Iterative modeling and experimentation		
	10. Use of modeling to select input parameters.	A quantitative model based on first principles used to determine Run 1 input parameters.[a,c] Model components explicitly linked to the determination of input parameters for six of the eight experiments.[a,b]
	11. Evaluation and revision of model based on analysis of experimental data.	Three revisions to model components.[a,b] Five model components developed after the first experiment.[a,b]
	12. Use of iterative modeling and experimentation to converge on high-performing input parameters.	Six model components deemed "primary."[a,b] Expert submitted a final recipe of input parameters nearly identical to his last run.[a]
	13. Strategic changes in approach to determining input parameters.	Three distinctly different approaches guided modeling in the beginning, middle, and end of the project.[a,b,c]
	14. Use of first principles throughout the solution process.	All but one model component directly based on first principles.[a,b]

[a]Evidence from model map analysis. [b]Evidence from notebook. [c]Evidence from think-aloud. [d]Evidence from post-project interview.

model for the VCVD learning system. These competencies may now be compared to the competencies demonstrated in student solutions as represented by model maps.

Assessment of Student Solutions

To address our second research question, Do the competencies demonstrated by the expert inform the assessment of student learning as verified by the examination of student work?, we have used the expert modeling competencies shown in Table 1 to assess the solutions of a low-performing and a high-performing team.

The next sections present the model maps representing the two teams' solutions. We present these solutions for three reasons. First, the examination of team solutions allows us to determine if the expert competencies can be used to differentiate quality of student solutions. Second, we begin to investigate the continuum of expertise demonstrated in the three solutions. Understanding this continuum of expertise allows us to frame instruction and assessment of student learning accordingly; that is, for any student team, instruction should be differentiated to afford the greatest advancement along the continuum possible. Third, due to the complex solution space, we believe we may discover alternative expert solution traits beyond those identified in this study. This knowledge can be used recursively to identify and inform the next stages of the expert study.

Summary of the student teams' solutions The model map of the low-performing team, labeled Team A, is shown in Figure 7. During the information gathering stage, Team A did

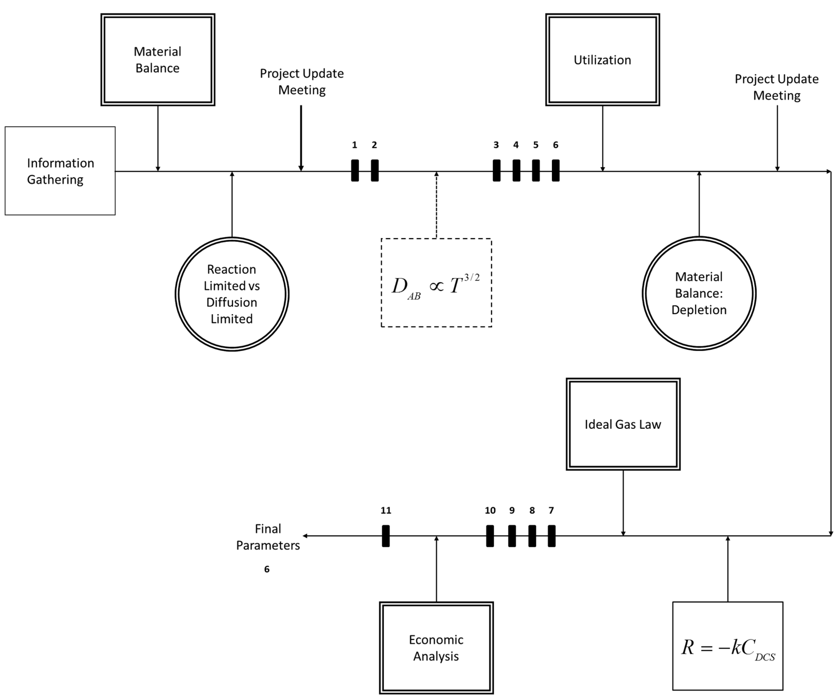

Figure 7 The model map representing the solution of student Team A (low performing).

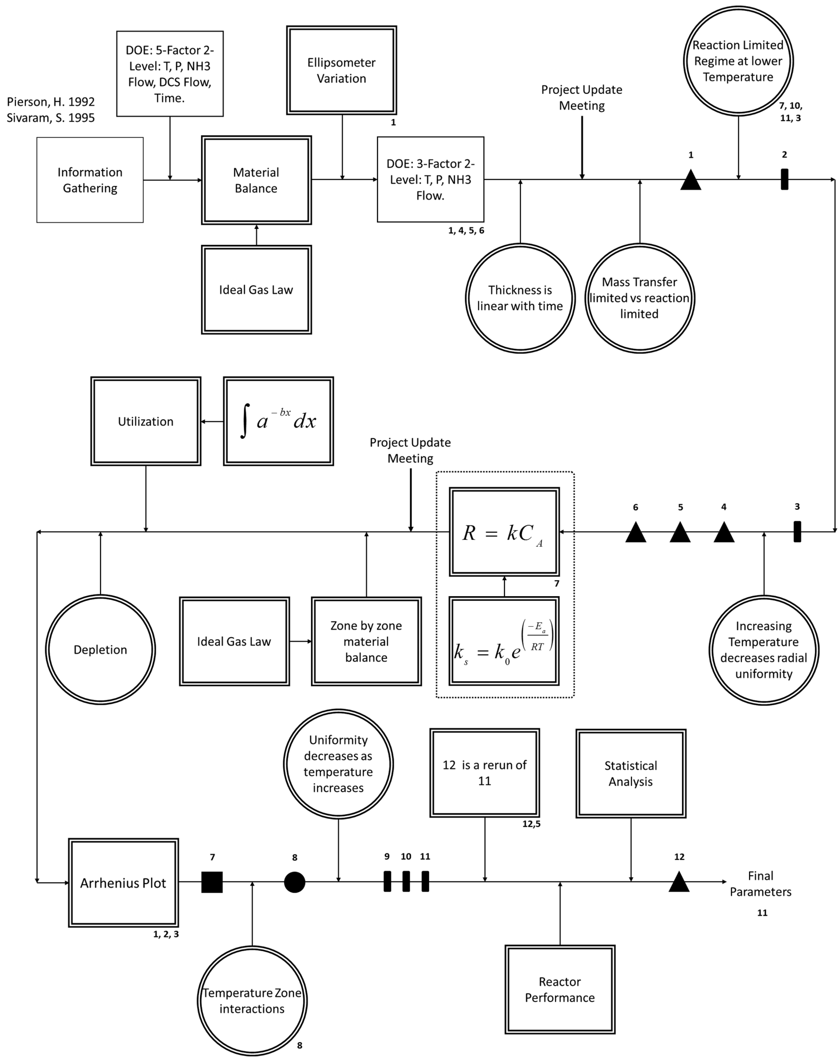

Figure 8 The model map representing the solution of student Team B (high performing).

not refer to any sources in their notebook. While formulating the problem, Team A developed two model components before their first experimental run. Regarding iterative modeling and experimentation, the team generated six model components, each in piecemeal fashion. That is, no model components are connected to each other and none lie directly along the central solution line. After completing 11 experimental runs, the team concluded the project by submitting input parameters from their sixth experiment as their final recipe of input parameters.

The model map of the high-performing team, labeled Team B, is shown in Figure 8. During information gathering, the team explicitly noted two sources from literature. The model map shows the development of seven model components during problem formulation before the first experimental run, all but one of those coming before the first project meeting. During iterative modeling and experimentation, Team B generated 15 more model components while performing 12 experimental runs. They concluded the project by submitting a final recipe of input parameters that was identical to that used to perform experimental Runs 11 and 12.

Evaluation of student performance using expert competencies When the student model maps are compared with the modeling competencies identified in the expert's solution, several differences are found between the teams, and between the students and the expert. Regarding information gathering, both teams cited fewer sources than did the expert; Team A cited no sources.

When framing the problem, Team A performed poorly compared with the expert's modeling efforts; they generated only two model components, neither of which were explicitly used to inform experimental runs (no run reference number is shown at the bottom right corner of the model).

Team B's early modeling effort, though, reflects the expert's approach regarding the number of model components developed and their future application to determine experimental input parameters. Two of Team A's model components in this stage signify their pursuit of solving the VCVD task using a DOE, similar to the approach considered by the expert. Correspondingly, the triangular run-type markers marking Runs 1 and 4–6 show that the team implemented their second DOE model component.

During the iterative modeling and experimentation stage, Team A developed a model component based on first principles to predict reaction rate ($R = kC_{DCS}$), but only after receiving guidance from the project supervisor in two meetings. This reaction rate model component was the same as one of the components in the expert's modeling cluster discussed above. Yet the team did not develop the additional model components needed to apply the reaction rate model to the VCVD task as did the expert. Consequently, they did not explicitly use their reaction rate model to inform any of their experimental runs. Furthermore, Team A did not reference any of their model components when justifying experimental run input parameters in their notebook. This loose connection between the modeling and experimentation is evidenced in the final recipe submitted by Team A. The recipe contained the same input parameters as they input for their sixth experiment. That is, the team was unable to improve the reactor's performance in the second half of their experiments.

During the iterative modeling and experimentation stage, Team B performed extensive modeling compared with Team A and the expert. After Run 6, the team developed a reaction rate model cluster based on first principles; the model cluster is identified with the dashed rectangle in Figure 8. The two model components in the cluster ($R{=}kC_A$ and $k_s{=}k_oe^{(E/\mathrm{RT})}$) are the same as two of the four model components in the expert's model cluster. Unlike Team A, Team B developed their model to a degree where it could be directly applied to determine the input parameters for experimental Run 7 (solid black run-type marker). As mentioned previously, the development and application of such modeling clusters suggest that the students in Team B possessed an interconnected and functional body of knowledge regarding fundamental chemical engineering concepts.

Similarly to the expert and Team A, Team B practiced iterative modeling and experimentation. Team B's model map shows that the team refined their modeling cluster related to Material Balance. They also developed four qualitative model components after beginning to perform experiments. These model components, such as "Increasing temperature decreases radial uniformity," are likely the result of the team's analysis of run data. Team B's convergence on an optimal solution is further evidence of its advanced application of iterative modeling and experimentation. That is, they submitted final process input parameters that were identical to those used to perform their last experiment.

Discussion

Competency Model in the VCVD Learning System

The list of expert competencies was useful in differentiating between the two team solutions and results were consistent with the previously identified low and high levels of student performance. Table 2 summarizes these comparisons.

Both student teams exhibited a subset of the competencies found in the expert solution; the high-performing team exhibited more expert-like traits than did the low-performing team. Understanding where each team is along this continuum can guide instructor feedback

Table 2 Evaluation of Team A and Team B's Solution Using the List of Modeling Competencies Demonstrated in the Expert's Solution

Solution stage	Modeling competency demonstrated	Team A (low performing)	Team B (high performing)
Information gathering			
	1. Identification of multiple sources	–	+
	2. Evaluation of information credibility and applicability	–	na
	3. Assimilation of information	na	na
Formulation of the problem			
	4. Identification of a critical aspect	na	na
	5. Conceptualization via interconnected model components	–	+
	6. Mathematization	na	+, quantitative model components applied
	7. Simplification	na	+, quantitative model components applied
	8. Solution	na	+, quantitative model components applied
	9. Modeling before experimentation	Two model components	Seven model components
Iterative modeling and experimentation			
	10. Modeling to select input parameters	–	+
	11. Evaluation and revision of model	+	+
	12. Convergence on high-performing input parameters	–	+
	13. Changes in strategic approach	na	–
	14. Use of first principles throughout the solution process	+	+

Note. – = little or no evidence found in the student solution; + = significant evidence found in the student solution; na = competencies that are unknown based solely on model maps analysis and therefore are not applicable.

in future projects. For instance, instruction of Team A might focus on some of the core aspects of the VCVD solution process that their solution lacked (e.g., a review of literature) and the application of prior learned content. Instruction for Team B, whose solution already embodied many of the expert traits, might focus on refining their solution by increasing their review of literature and by focusing on evaluating solution strategies earlier in the solution process (Team B started their DOE plan but abandoned it to pursue a theoretical approach). Team B's solution also provided insight into additional solution traits that we conjecture represent high-quality solutions.

The competency model shown in Table 1 contains modeling competencies identified from analyzing the expert's solution at both the coarse- and fine-grain level. In this article we assessed student solutions on the basis of the competency model using only the coarse-level analysis of model maps. This coarse-level analysis aligns with the level of assessment that is feasible at large-scale. Information regarding the expert's solution at a finer level is useful in developing a better understanding of the modeling competencies the expert developed.

Study Limitations

The first limitation of this study is that the expert worked alone while the students worked on a team. When working to solve complex problems, teams are beneficial and change the nature of the solution process (Brophy, 2006; Wiley & Jolly, 2003; Ullman, 2009).

We also studied the solution of only one expert. The VCVD task is complex and has a large solution space. Thus we expect to see differences in modeling strategies as we observe additional expert teams complete this task. For example, we may encounter expert solutions that primarily rely on DOE to solve the VCVD task. The expert considered a DOE approach in this study as indicated in his model map by a non-operationalized DOE model component that he developed while formulating the problem. In the post-project interview, he indicated that he considered DOE a common approach used in industry to solve similar process development tasks. Examination of the model map generated by Team B also provides insight into additional competencies. For example, they performed statistical analysis to characterize variation in the VCVD process and in the measurement tool. We view these solution features as likely representing a high-quality solution, but they were not present in the expert's solution. A wider range of expert solutions would provide a more complete list of modeling competencies for the VCVD process development task.

An additional limitation is the study's focus on characterizing modeling competencies. While such a focus was necessary in the early developmental stages of our assessment framework, we have witnessed many other competencies in student solutions to this task that are not captured by the model maps analysis method. These include intra- and interpersonal, project management, and metacognitive competencies. Future work could focus on developing ways to identify such student competencies. However, for analysis of some of these competencies, study of experts in teams is needed.

Finally, while examination of the student teams' solutions demonstrated the utility of the competency model and our framework, more work is still needed to streamline the assessment framework so that it may easily be applied to a large number of student solutions in the VCVD learning system to yield numerical scores.

Implications for Research and Practice

Industrially situated, computer-enabled learning environments can be designed to provide students experiences within the university curriculum that reflect professional practice. Since the simulation can easily generate authentic data, students are afforded the opportunity to work in teams and perform cognitive processes that they will need in practice. We view this type of learning environment as fundamentally different from and complementary to common modes of lecture and the teaching laboratory. Such environments provide rich opportunities for student learning, but the type of higher-order thinking that is elicited is difficult to assess. While we have described a framework for the assessment of student learning in one such learning environment, the VCVD learning system, we suggest five areas where this study has more general implications for research and practice in engineering education.

First, although this study is limited to one specific learning environment, we suggest the comparison of competencies between the expert and the student teams is useful for engineering educators when crafting design problems and other engineering project work. Educators may particularly want to develop instructional activities that require students to demonstrate competencies shown by the expert in this study. Such activities should facilitate feedback and scaffolding that encourage students to be thorough and critically compare sources in the information gathering stage; they emphasize model development before experimentation and encourage students to use a conceptual systems perspective to inform design strategies in the problem formulation stage, and they help students use iterative model development and experimentation to converge on a final design or project solution.

The instructional design approach shown in Figure 2b begins by identifying a task in the wild and then adapting it to the academic setting while being mindful of the limits of the cognitive resources possessed by students. We have argued that the cultivation of students' ability to apply their knowledge and skills in the wild is most effectively developed through engagement in tasks that reflect as closely as possible the authentic environments of professional practice. Such an approach should deliberately include alignment among instructional activities and obtaining evidence of student competencies through assessment. This article describes a case where the components of evidence-centered design are intentionally incorporated into a learning system using this approach. This case serves as a model example for instructional design in engineering education. The approach can be used not only by developers of computer-enhanced learning environments in other domains but also, more generally, in open-ended coursework focused on bringing real-world engineering projects and problems into the curriculum, such as in the capstone projects sequence found in most engineering programs. As demonstrated in the use of model maps, the heart of this intentional alignment is the development of evidence and competency models. We assert that the use of industrially situated learning environments, where the task is constructively aligned with evidence of student learning and target competencies, can promote higher-level thinking and can better help students develop the knowledge and skills required in engineering practice.

We have described an industrially situated, computer-enabled learning environment that develops student's engineering knowledge and skills. We suggest such computer-enabled learning environments can be useful for researchers interested in studying the development of expertise in complex, authentic engineering contexts. The virtual environment facilitates such studies in three ways. First it provides a common, controlled system to all participants where the experimental data for a fixed set of run parameters are similar and within the range of prescribed experimental error. The task is open ended with many possible paths to completion. Therefore, in comparing experts and novices, and experts among themselves, researchers can focus on differences in terms of design approach and cognition. Second, with virtual experiments, participants can explore a larger area in the design space in a fixed amount of time than would be possible working with a physical system. This virtual aspect makes it tractable to find experts who are willing to complete an entire project rather than just a portion of it, as is commonly reported in studies of expert engineers. Third, although not reported in this article, the computer program behind the simulation can provide an objective quality measure of the final recipe of input parameters as submitted by all participants. These recipes can be evaluated in terms of the performance metrics since values of those metrics can be calculated directly from the first principles model that drives the simulation. The computer output provides an objective measure of the quality of the final design that can be compared among different participants and approaches. Such expert studies assume that the virtual task sufficiently mirrors industrial practice, an assumption which should be member checked through interviewing practicing engineers.

Examination of the expert's solution path, especially in the problem formulation stage, shows how he operationalized core concepts to develop a modeling strategy that reflected the engineering objectives and how components of the model are then developed, quantified, and mathematized to provide information useful for completing the design task. Instructors must consider if the ways students learn modeling in science and engineering science courses best develops the knowledge and skills that they need to contextually apply modeling. Specifically, we need to consider whether our instructional methods afford them the ability not only to be procedurally competent within a given subject, but also to recall appropriate concepts from a broad foundation of course work and to recognize how pertinent concepts may be applied to complete a design task. These issues are partly addressed in recent research in engineering education and the learning sciences. We believe that to be more effective, the core curriculum must be better integrated, give more attention to conceptual learning (Streveler, Litzinger, Miller, & Steif, 2008), and provide more expansive framing of content (Engle, Lam, Meyer, & Nix, 2012). How such curricular emphasis allows students to transfer modeling skills from their course work to complex, authentic tasks and practical projects is an open topic for engineering education research.

Finally, this comparative case study contributes to our understanding of the role of models and modeling in the context of chemical engineering project work. Models are both tools applied in the process of engineering design and products of the design process. Philosophers of science have observed the centrality of models and model formulation to the progress of science (Frigg & Hartmann, 2012). Science educators have also suggested that models and modeling can serve as a bridge between science education and engineering education (National Research Council, 2011). We contend that from high school, through post-secondary education, and throughout the years of professional practice a scientist's or engineer's model-related practices develop. Further research on modeling in complex, authentic engineering tasks can influence learning research and engineering and science education while providing insights on how complex abilities develop across the years.

Acknowledgments

The authors are grateful to the expert and students who participated in the study. This material is based upon work supported by the National Science Foundation under grants DUE 0717905 and EEC 1160353 and on support for Edith Gummer while serving at the National Science Foundation. The authors also acknowledge Eileen Otis for insights into ethnography, Audrey Champagne for discussions about the implications of this study, and Debra Gilbuena for helping in many ways. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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Authors

Benjamin U. Sherrett performed this work as a graduate research assistant in the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University, 204 Rogers Hall, Corvallis, OR 97331; sherretb@onid.orst.edu.

Erick J. Nefcy is a graduate research assistant in the School of Chemical, Biological, and Environmental Engineering at Oregon State University, 102 Gleeson Hall, Corvallis, OR 97331; nefcye@onid.orst.edu.

Edith S. Gummer is a senior research scientist at WestEd, 1350 Connecticut Avenue NW, Suite 1050, Washington, DC 20036; egummer@wested.org.

Milo D. Koretsky is a professor of chemical engineering in the School of Chemical, Biological, and Environmental Engineering at Oregon State University, 102 Gleeson Hall, Corvallis, OR 97331; milo.koretsky@oregonstate.edu.