AC 2011-2255: CHARACTERIZATION OF STUDENT MODEL DEVELOPMENT IN PHYSICAL AND VIRTUAL LABORATORIES

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Acknowledgments: The authors are grateful for support provided by the National Science Foundation's Course, Curriculum and Laboratory Improvement Program, under Phase 2 grant DUE-0717905. 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 National Science Foundation.

Characterization of Student Model Development in Physical and Virtual Laboratories

Abstract

This study characterizes student teams' use of models as they proceed through three laboratory projects in the first quarter of the capstone laboratory sequence in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. Two of the laboratories are physical laboratories, based on the unit processes of heat exchange and ion exchange. Sandwiched between these two laboratories, students undertake a virtual laboratory project. The virtual laboratory is used to simulate complex or expensive tools that are not readily available for use by undergraduate students, but are more representative of industrial systems. In this study, a virtual chemical vapor deposition laboratory is used. The instructional design of the virtual laboratory project is intended to complement the physical laboratory projects in the curriculum. Students interact with a three-dimensional computer simulation to gather data. In the virtual mode, there is lower cognitive demand required to physically perform the actual experiments, affording students the opportunity to build a rich experimental design based on interpretation and iteration. Previously, we have reported a graphical method that has been developed, termed Model Development and Usage Representations. These maps characterize student teams' model development as they proceed through a laboratory project. In this paper, the Model Representations for 15 teams are examined as they complete physical and virtual laboratory projects in the senior year of the curriculum. Analysis of the Model Representation confirms that the virtual laboratory project affords students a richer opportunity for model development, modification, and use of evidence-based reasoning.

Introduction

As technology is integrated into classroom instruction, virtual laboratories have been receiving more attention as an alternative mode to engage students and promote learning.[1] Most commonly, the virtual laboratory is used as an alternative mode to deliver the corresponding physical laboratory by simulating a similar set of activities; we term this type an *analogous virtual laboratory*. For example, Texas Tech University has developed a virtual laboratory based on a double-pipe heat exchanger.[2] The LabVIEW based user interface creates a realistic replica of the interface on the corresponding physical experiment they use in the unit operations laboratory. Students collect temperature measurements and compare heat transfer in co-current and counter-current flow geometries. In analogous virtual laboratories, systematic studies can be conducted to assess learning in the virtual mode and compare it to learning in the physical mode. In this manner, research shows equivalent and often greater learning gains in the virtual mode.[2-6] In this paper, we address an industrially situated virtual laboratory with *no direct analog* to the university instruction laboratory. Assessment of student learning for these industrially situated laboratories is very limited, in part because there is not an obvious comparison group for such a study as with the *analogous virtual laboratories* described above.

This study compares student learning in an industrially situated virtual laboratory project with *no direct analog* to two senior level physical laboratory projects in the same senior course.

Specifically, this study investigates the student model development and usage in the three laboratories. Model development and usage is an important skill utilized by engineers when completing open-ended, ill-structured tasks. Gilbert and Boulter define a model as a representation of a phenomenon produced to develop a greater understanding of said phenomenon.[7] In our instructional design, the virtual laboratory project allows students the opportunity for iterative experimental design, analysis and interpretation, and redesign.[8] This iterative process affords the students the opportunity to develop and augment pertinent models for use in their solution process.

This study is part of an ongoing research effort to study the perceptions of students and instructors and the nature of learning elicited in this industrially situated virtual laboratory project.[9,10] By determining how students develop awareness and knowledge in a virtual environment, the role of the virtual laboratory as an effective curricular tool can be constructed. While the results presented in this paper suggest the virtual laboratory project affords students greater opportunity for model development, we believe that they complement physical laboratories and should not replace them. Physical laboratory projects encourage development of robust haptic skills that are not the focus of the present investigation.

Physical and Virtual Laboratories in the Study

The Virtual Chemical Vapor Deposition (CVD) Laboratory Project that is the focus of this study is based on a rigorous numerical simulation of an industrial chemical vapor deposition reactor to which random process and measurement error are added. This equipment is used to deposit a film of silicon nitride by flowing dichlorosilane and ammonia gases through the reactor at high temperature and low pressure. Students are tasked with optimizing the process to achieve a target thickness, high uniformity and high reactant utilization - though the extent of this optimization is chosen by the students. The student teams choose the parameters to run the reactor and the locations and wafers to measure. In the studied curriculum, the Virtual CVD Laboratory Project is accompanied by the Virtual Bioreactor (BioR) Laboratory Project. Approximately half the students select each virtual laboratory project. In the 2009 assignment of the Virtual CVD Laboratory Project, students are tasked with optimizing two separate, and somewhat different, reactors. This serves to test the robustness of the student solution process. Details regarding these two laboratory projects, their instructional design, and protocol analysis of student learning and perception have been previously published.[8-12]

Two physical laboratory projects sandwich the virtual laboratory project in this course. The first of the two is a Heat Exchange Laboratory Project which tasks students with characterizing a system used to recover steam energy. Students achieve this by adjusting flow rates and by investigating the differences between counter-current and co-current flow. The first session focuses on an introduction to the equipment and the second session is directed to experimental measurements using the experimental design created by the students. The second laboratory project revolves around the use of an ion exchange tower for the removal of calcium in water. The first session in this project involves calibrating the calcium detection equipment, the second session involves calcium removal via ion exchange, and the third session characterizes the resin regeneration process. Both physical laboratory projects provide an industrially situated context. In the case of the heat exchange laboratory project, students are said to be part of an energy recovery team tasked with saving their parent company money by utilizing waste steam energy.

In the Ion Exchange Laboratory Project, students characterize an ion exchange resin and use that characterization to design a waste stream treatment process.

Participants and Methods

Student participants were from the same cohort in the first term of the senior capstone laboratory sequence at Oregon State University. This class included 27 students majoring in bioengineering, 45 students majoring in chemical engineering, and 9 students majoring in environmental engineering. These students were assembled into 27 three student teams whom all participated in the physical laboratories. They had a choice between the two virtual laboratories, 15 teams worked on the Virtual CVD Laboratory Project (45 students) and 12 teams worked on the Virtual BioR Laboratory Project (36 students). This paper focuses on analysis of students who chose the Virtual CVD Laboratory Project but similar results are observed for the set that chose the Virtual BioR Laboratory Project. This research was approved by the institutional review board and the results reported here are from participants that signed informed consent forms.

In this study, Model Development and Usage Representations are used to provide a visual depiction of student modeling during the three laboratory projects. These maps categorize the model component type (quantitative, qualitative, statistical or empirical), their degree of utilization (operationalized, abandoned or not engaged), their correctness, and the experimental runs to which they are relevant. This information is chronologically arranged along with experimental runs, emotional responses and instructor consultation to give an appropriate context to the team's work. This information is derived from student work in the form of laboratory notes, update reports, final reports, oral presentation and experimental parameters which, for the Virtual CVD Laboratory Project, are retrieved from an internal database. Model Development and Usage Representations have been generated for the Heat Exchange, Virtual Chemical Vapor Deposition, and the Ion Exchange Laboratory Projects. In total, between the three laboratory projects, 42 Model Representations have been completed and analyzed. A brief description of Model Development and Usage Representation is provided below; more detail is available in Seniow et al.'s work.[12]

Model Development and Usage Representation

Student journals and memorandum reports are the primary source of information as they contain all notes, references, results and calculations relevant to the project and its development over time. Model components are identified in student journals and verified in other sources (reports, run data, oral presentations). A student researcher assembles this information and constructs the preliminary Model Representation. A faculty member, a domain expert, then reviews and evaluates this information for accuracy and correctness. The separation of the student researcher's production of the preliminary Model Representation and the domain expert's review is done intentionally to ensure consistency and reliability. The two meet and discuss until consensus is reached. A few features germane to this study are highlighted below.

Model Components

Modeling components are identified in student work when it is clear that the use of this component furthered, or intended to further, the teams understanding of the project environment. Once the component is identified, a description or mathematical expression is added to the Model Representation. Quantitative Model Components, characterized by the use of mathematical expressions or reasoning, are placed inside squares, while Qualitative Model Components, characterized by descriptive or intuitive mechanisms, are placed inside circles. To further describe the fundamental nature of a model component, an ‘S’ or ‘E’ is placed inside the model component to indicate the presence of a model component which is statistical or empirical in nature, respectively.

Figure 1 displays the different types of modeling components. The color of the model component represents the type or level of engagement associated with the particular model component. A green model component represents a model which has been operationalized and retained by the team. A red model component represents a model component which has been considered, and in some cases utilized and deemed irrelevant. This commonly occurs when mathematical errors prevent a model component’s full usage, when the data contradicts the hypothesis posed by the model, or when a more correct or relevant version of the same model component is discovered later. Black model components are considered to be “not engaged”. These model components show up in team reports and notebooks without any evidence of utilization in mathematical work, changes evident in their run parameters, or otherwise. Model components which are placed on the center line are considered central to the team’s approach to the project and are designated as “Primary Model Components”. Models which lie outside the center line, connected by inward arrows are considered “Secondary Model Components”. Some model components are presented as groups which connect to each other vertically. These model components are considered to be chunked together by the student team. This formation is indicative of high level modeling.

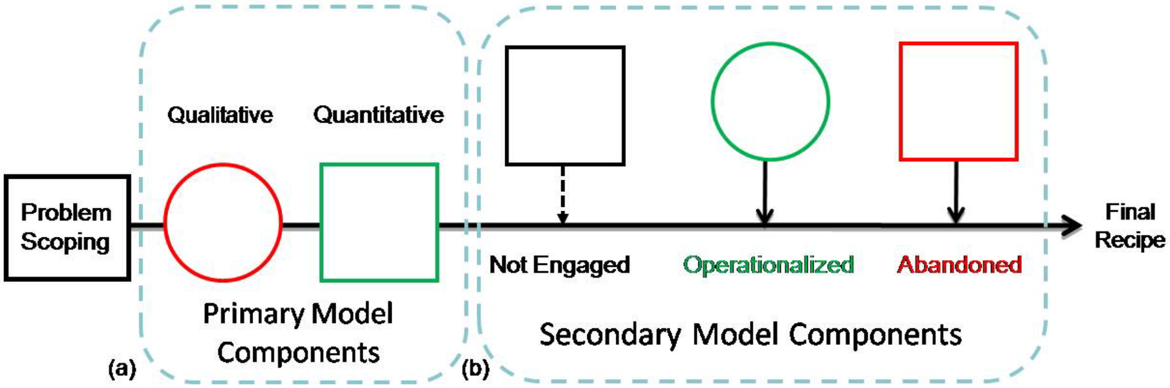
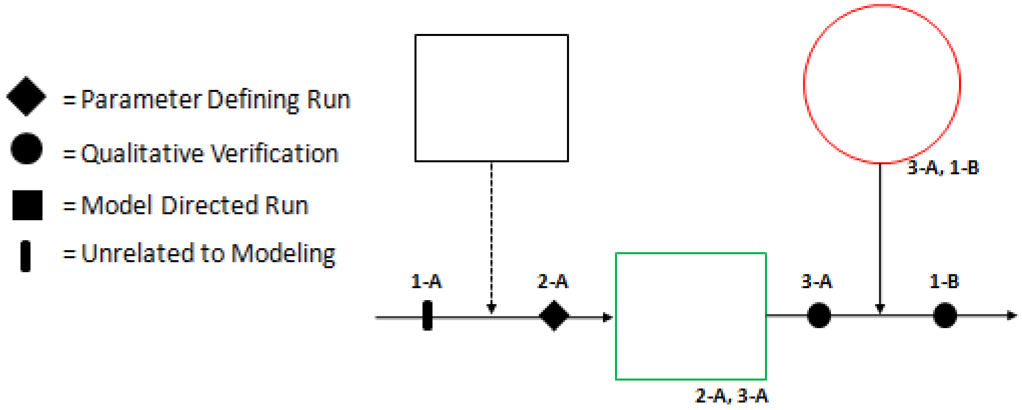


Figure 1. **Primary and Secondary Model Components.** Part (a) shows both qualitative (circle) and quantitative (box) Primary Model Components, which sit on the center line, while part (b) shows Secondary Model Components, which in addition to Operationalized (in green) and Abandoned (in red) can be Not Engaged (in black and with a dashed connecting arrow) and are connected to the center line.

<u>Experimental Run Markers</u>

Experimental runs are also included in the Model Representation. Experimental run markers appear on the center line with an accompanying run number. As shown in Figure 2(a), the symbol indicates the type of run performed. These include “Parameter Defining” Runs (a run which was used to collect data necessary to obtain a numerical model parameter), “Model

Directed" Runs (runs having parameters produced by a student model), or "Qualitative Verification" Runs (runs which confirm or contradict qualitative model predictions). Experimental runs which cannot be classified in any of these categories are said to have no relation to modeling and have their own appropriate run marker. Run numbers which appear near model components, seen in Figure 2(b), indicate the relevance of that run in the development or use of that model component. To properly characterize the use of two reactors in the 2009 Virtual CVD Laboratory Project, the run numbers have been augmented to include a hyphenated "A" or "B" to indicate which reactor the team used for the experimental run in question. One difficulty arose in applying this methodology to the physical laboratory projects. It was often difficult to discern when the model components were identified relative to the experimental runs. Therefore, run numbers are omitted and modeling elements are characterized by laboratory session.



(a) Run markers by motive **(b) Example Model Representation including runs**

Figure 2. **Run Marker Types and Notation.** Part (a) lists four motives for conducting runs as they relate to modeling while part (b) provides an example of how runs and model components are integrated into the Model Representation.

Results and Discussion

Model Representations for one of the teams in the cohort, Group A, are shown for each of the three laboratories they completed. The ways this specific team engages in modeling for each of the laboratories can be compared. This analysis is followed by characterization of some features for the entire cohort.

Figure 3 shows the Model Representation for the Heat Exchange Laboratory Project, the first of the term. Over the duration of the project, the team used four quantitative models and two qualitative models. One of the quantitative models was abandoned (red). This representation illustrates how this physical laboratory project reinforced concepts from the transport and thermodynamics courses in the curriculum including sensible and latent heat and the overall heat transfer coefficient. The qualitative modeling was used to reason through the effect of configuration and parameter changes. Not surprisingly for this targeted instructional design, most teams in the class had very similar model components for this laboratory project. The most noted variation was that two teams used insulation in their design.

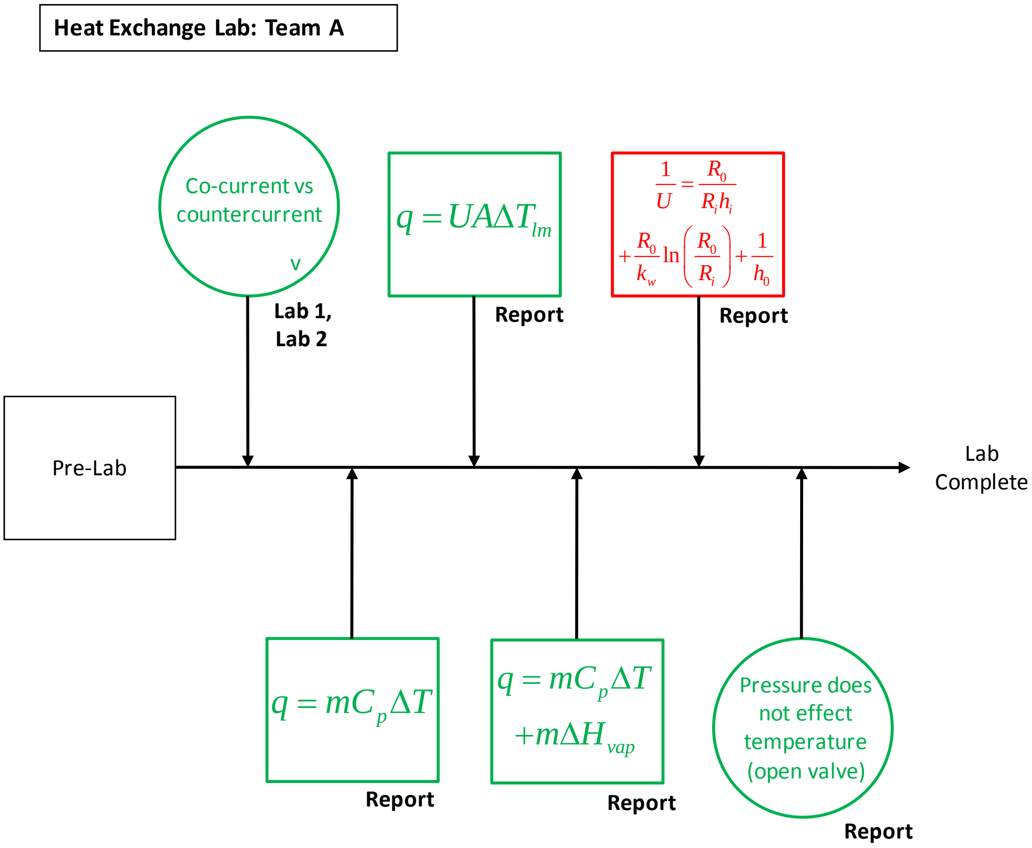


Figure 3: The Model Development and Usage Representation Map for Team A's Heat Exchange Laboratory Project. The sensible heat equation (the second component) and the conductance equation (the third component) are the two most commonly used components in this project

The Model Representation of this same team for the Ion Exchange Laboratory Project is shown in Figure 4. This physical laboratory project was the last in the term. Team A uses 3 quantitative and 3 qualitative model components. Two of the quantitative models are clearly incorrect. All teams in the cohort had difficulty with this breakthrough time estimation. Team A is uncommon in that they conceptually identified the source of their error with a qualitative model "Virgin Resin Effects." Much more commonly, teams mistakenly attributed it to experimental error. The overall flow of model component development mirrors closely the specific experimental procedures provided in the assignment. One element of transfer, however, is noted - the calibration of the rotameter. This process was suggested by the instructor late in the Heat Exchange Laboratory Project, but was not specified for the Ion Exchange Project. Nonetheless, thirteen of the fifteen teams correctly calibrated the rotameter. This example shows the use of the physical laboratories in developing procedural knowledge. This area of development is an important component to student learning, but not the focus of this paper.

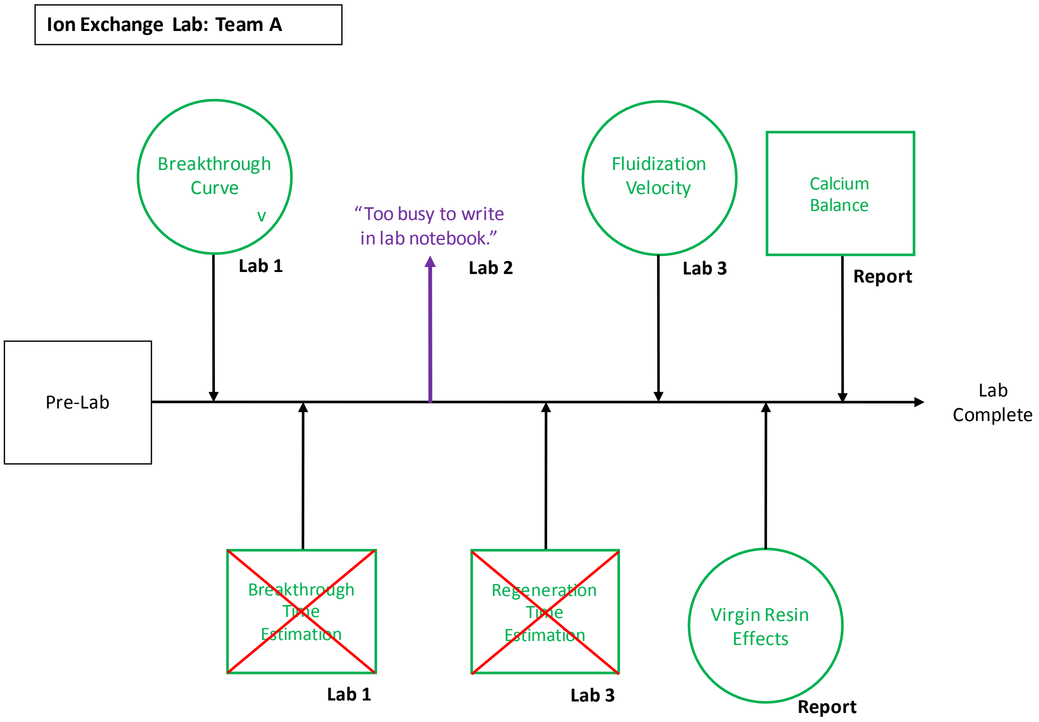


Figure 4: Team A's Ion Exchange Laboratory Project Model Development and Usage Representation. The quoted response is evidence of the in-lab time restraints.

Both physical laboratories were characterized by similar Model Representations for the entire cohort. Among these depictions, one can surmise those teams that had innovative experimental (e.g., insulation) or analysis (e.g., virgin resin effects) approaches. But, in general, these differences were relatively small changes relative to a common solution approach.

Figure 5 shows the Model Representation for this same team in the Virtual CVD Laboratory Project. Team A uses 15 quantitative and 7 qualitative model components. Two of the components were abandoned. Five runs were "model directed" meaning the team used an engineering science model to predict the input values for the reactor run parameters. Two of the runs were "parameter defining" meaning they utilize data from the run to find the value for a parameter in the model. Several of the model components are linked together, suggesting a "chunking" of these components.

This team design approach started by using Design of Experiments, then moved to reactor modeling to predict the input parameters. Several times they analyzed data to attend to variation in the process and measurement tools. Throughout the project, they maintained a very high level of self-monitoring and metacognition. This team's particular solution method was assessed as

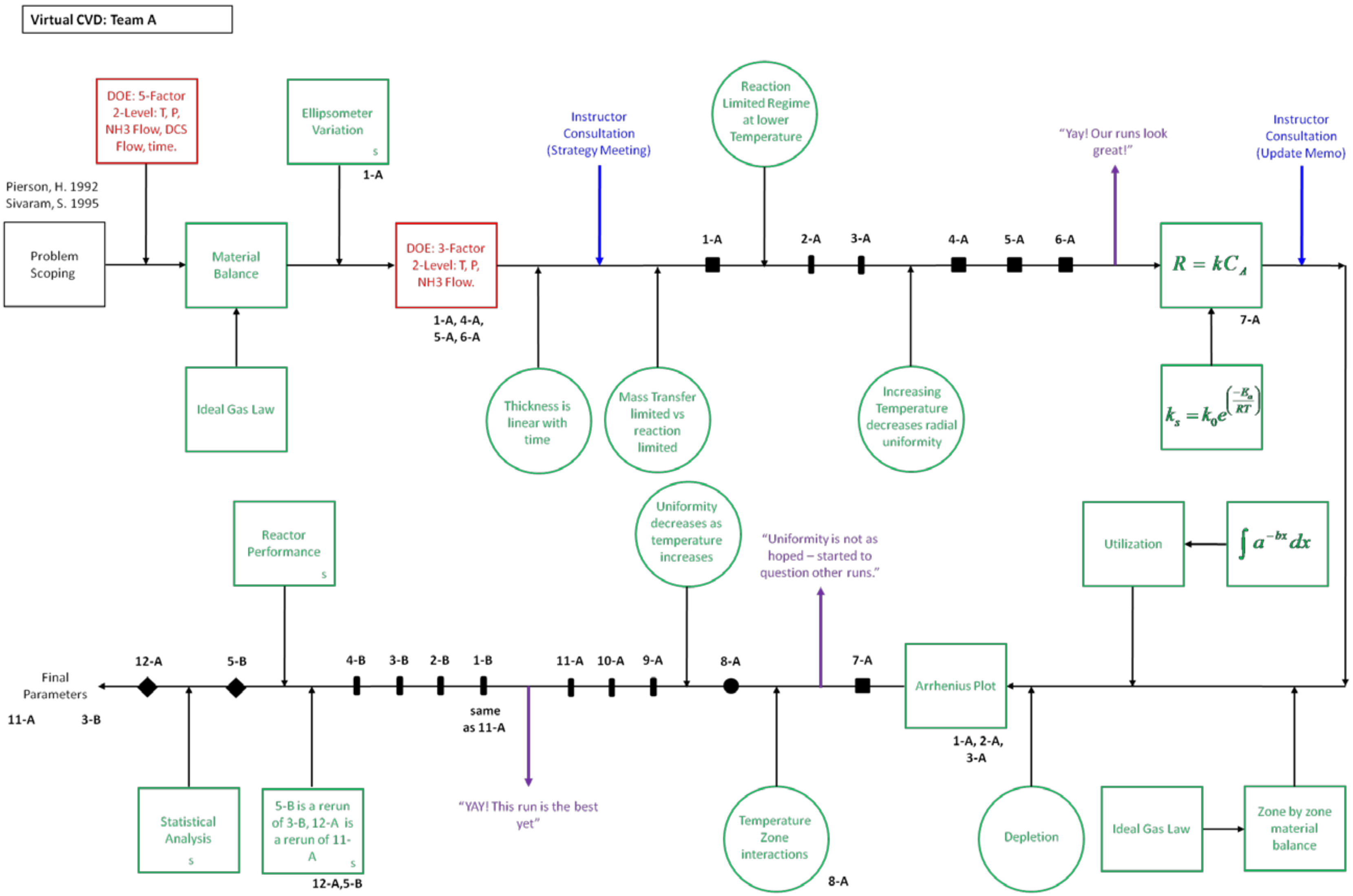


Figure 5: Team A's Virtual CVD Model Representation and Usage Map

strong by the course instructor. Other teams had very different approaches. In fact all Model Representations were distinctly unique, and specific components varied widely. These characteristics are distinctly different from the two physical laboratories

Table 1 shows a statistical summary of elements of the Model Representations for the entire cohort. The results are similar to Team A. Many more quantitative and qualitative model components are used during the Virtual CVD Laboratory Project than for each of the physical laboratories. Additionally, the range is much greater.

Table 1. Analysis of Model Representations from virtual and physical laboratories

	Virtual Lab		Heat Exchange		Ion Exchange	
	Average	Range	Average	Range	Average	Range
Total Model Components Used	13.3	8 - 20	3.9	2 - 6	4.9	3 - 7
Quantitative Model Components	9.3	6 - 16	3.2	2 - 5	3.3	3 - 4
Qualitative Model Components	3.9	1 - 8	0.7	0 - 2	1.5	0 - 3
Operationalized Model Components	10.2	6 - 20	3.8	2 - 5	4.8	3 - 7
Incorrect Model Components	1.3	0 - 4	0.2	0 - 1	1.3	0 - 2
Models Directed Runs	1	0 - 5	0.5	0 - 5	0	0
Parameter Defining Runs	1.2	0 - 3	9.1	6 - 17	2	2

The open ended, ill-structured nature of the Virtual CVD Laboratory Project allows student teams to develop a solution in a creative way and encompasses a wide spectrum of knowledge and skills. The 2009 cohort developed 44 distinct model elements in their efforts to reach a suitable solution. Of these modeling elements, 18 were quantitative and 26 were qualitative. Two of these models fell under the ‘empirical’ description, one was considered ‘visual’ in nature, and three were ‘statistical’. In contrast, the Heat Exchange Laboratory Project produced 12 unique model elements; seven of which were quantitative while the other five were qualitative. One can be considered a visual model component and two others can be counted as statistical model components. For the Ion Exchange Laboratory Project, 12 modeling components were used. Of these 12, five were quantitative, seven were qualitative, and one could be considered a visual model component.

The Virtual CVD Laboratory Project investigated in this study was not designed as a technology replacement for a traditional laboratory experience. Rather, it affords the opportunity for students to experience thinking and solving problems that are industrially situated and are not available in current university curricula. Because the experiments are virtual, they are easy and quick for students to perform. This aspect affords students unusual depth of thought as they are not constrained by the haptic elements needed to make measurements but rather are able to plan runs and analyze results in the iterative experimental design process. In this way, it is not the direct interaction with the virtual laboratory where the majority of learning occurs, but rather in the students’ engagement with multiple instances of the dynamically generated data that the technology enables. Comparison of Model Representations between this virtual laboratory projects and two physical laboratory projects support the hypothesis that students are experiencing a rich opportunity at iterative design and integrated model development.

Conclusion

Through the mapping of student model components, their usage in virtual and physical laboratories was characterized. The hands-on, directed nature of the physical laboratory projects led to similar project approaches among the 15 teams. Through the use of iterative inquiry, student teams in the virtual laboratory project utilize their run data in the constant creation, revision and utilization of modeling components. This leads to a wide variety of project solution paths. Overall, this preliminary result shows that virtual laboratory project experience is valuable to students, as it provide an environment that affords the development of rich model-based solutions. It must be kept in mind that physical laboratories will always have an important place in the curriculum of an engineering student, and as such, it is encouraged that both types of laboratory projects are utilized.

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