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The Interplay Between Engineering Students' Modeling and Simulation Practices and Their Use of External Representations: An Exploratory Study

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The Interplay between Engineering Students’ Modeling and Simulation Practices and their use of External Representations: An Exploratory Study (Research)

Background and Motivation

Advances in computer and information technology facilitate innovation and education in science and engineering by enabling the processing, simulation, and visualization of unprecedented amounts of data. Modern computational tools allow us to address complex problems affecting health, energy, security, and overall quality of life, and future scientists and engineers will need to be prepared to exploit these tools to generate effective solutions to human challenges. Thus, the ability to use and create modern computational tools derived from and validated by experimental data is required to support engineering design and problem solving in our fast-changing and global society.

This study explores both how students engage in experimentation strategies and how they combine those strategies with the modeling and simulation process. Specifically, this study will identify how students model phenomena and solve a design problem, starting from experimental data. The research questions are: (1) How do students use external representations in each step of the modeling and simulation process? (2) How do students’ implementations of the modeling and simulation process relate to the quality of their battery system design?

Representations in Science and Engineering

In educational contexts, the use of graphical representations has been identified as a way to enhance engineering problem-solving and scientific inquiry skills [1], and to make the content accessible to students in a more learnable or concise way [2]. Research on graphical representations in education has been investigated in mathematics [3], physics [4-6], chemistry [7,8], biology [9-11], and engineering [2,12-15], among other STEM fields. However, research that describes the role of representations in education has shown inconclusive results concerning effective ways of using these tools meaningfully [16,17].

Findings from studies that have focused on representational abilities among practitioners and researchers have also shown conflicting results. For example, studies that compared novices and experts revealed that experts usually use representations proficiently as tools together with domain knowledge [8,13,18]. Similar studies (i.e. [19,20]) found that experts recalled elements on graphs in patterns based on principles rather than surface features, while novices tended to recall based on surface features [8]; that experts used these devices as tools with which to think [7,8,21]; and that differences in searches between novices and experts lie in dissimilar problem spaces [22].

Contrasting research in the area of ecology has shown that practicing scientists and engineers demonstrated no expertise in reading representations taken from introductory university textbooks [9]. In contrast, when these experienced individuals read their own representations, these representations provided them transparent access to actual real-world situations [9]. The findings suggest that a comprehension of representations is not an act of staring at the graphs to infer their meanings. Rather, the graphs are seen as sites where disclosures occur [7,9], “entailing [more of] an articulation of a familiar world than inferring something new” [9]. Roth’s studies suggest that the process of individuals creating their own representations may be more accessible for learners than using unfamiliar ones. Thus, this study investigates the relationship between students’ self-generated representations and their performance in a modeling task.

Methods

The context of the study

Participants of this exploratory study include 35 undergraduate and graduate students from a materials science course at a Midwestern University. These students were engaged in experimentation and modeling practices in the context of rechargeable batteries. The course consists of a theoretical component and a practical component. In the theoretical component, students learn about basic electrochemistry theory, principles of electrochemical devices, and electroactive materials as used in rechargeable battery systems. The practical component provides industry-standard analytical and computational modeling techniques by teaching students the practical aspects of battery fabrication. The procedures of the study were embedded in the practical component of the course. As part of a final project, students modeled and analyzed a graded porous electrode to be used as part of a rechargeable battery system. The individually-submitted course assignments served as the raw data used to examine students' modeling and simulation practices.

Data Collection

For part of the final course project, students were asked to design a rechargeable battery system able to operate under specific conditions in several different applications. For example, one team designed a battery to power an electric lawn mower for at least 30 minutes of operation. Another team designed a battery able to support 4 x 24 h of charge in a cell phone. This semester, 35 different projects were submitted and analyzed. To guide the students during the projects, the instructor provided a detailed assessment rubric, as well as some general guidelines for each project. These guidelines included recommendations for viability analysis, literature review, model validation, optimal electrolyte/salt concentration, and specific guidelines depending on the type of technology selected. No recommendations concerning the use of representations was included. As mentioned on the rubric, the projects were graded based on the students' rationale about each step of the following modeling and simulation process adapted from Shiflet and Shiflet [23]: (a) problem description, (b) problem framing, (c) model configuration, (d) validation of the model, (e) discussion of the solution and results, and (f) conclusions and recommendations. The 35 final projects were reviewed and graded by the instructor via the rubric and then submitted to our research team for data analysis and discussion. This study employs three main data sources: students' projects submissions, student project scores using the assessment rubric, and the instructor's comments on the scoring for each project.

Role of the Researchers

During the design stage, the instructor and the research team worked together throughout the implementation of the project and the data collection. First, one senior researcher met with the course instructor early in the semester to identify the modeling and simulation skills to be integrated as part of the course. Then, based on those simulation skills, the course instructor defined the projects. Next, during a working session, the course instructor and the senior researcher jointly defined the project template and the corresponding rubric. The project template and the rubric were revised three times for proper alignment. The final grading rubric is included in the Appendix. During the data analysis stage, three investigators worked together to jointly analyze the data following procedures of validity and reliability. Once the data analysis was completed by the investigators, the course instructor was provided with an opportunity to provide feedback on the overall findings of the study.

Data Analysis

The data analysis was comprised of two separate steps. First, we reviewed each project to identify the number and type of external representations used by the students within each step of the process. This first stage resulted in a preliminary codebook. Second, we evaluated student implementation of the modeling and simulation process, considering both the students' representations and the instructor's comments. In the third stage, we compared the generated representations to the overall score, which was assessed by the instructor using the rubric.

The identification and characterization process of external representations proceeded as follows. Two researchers explored each of the documents and defined five different categories of representations found in the reports: images, plots, tables, equations, and flow charts (see Table 1 below). Two researchers first coded 20 percent (7 out of 35) of the project documents separately. One report document was selected at random from each of the student teams, resulting in one document per project. After an initial meeting, the researchers noticed a need for two different types of mathematical representations: equations and calculations. Equations were primarily used to express how some variables behave under certain conditions. Calculations were used to demonstrate how students defined important parameters of the system. As a consequence, the representations codebook was refined to use six different types of representations: the first five already mentioned plus calculations.

Table 1. Types of representations and definitions

Type	Description
Images	Photographs, diagrams, schematics, and other images used to illustrate a concept or depict a design choice. Images do not include data.
Plots	Plots, charts, graphs, and phase diagrams used to depict/explain pre-existing or student-generated quantitative data.
Tables	Formatted tables used to organize parameters, results, and other project information.
Equations	General equations (i.e. without values) used to relate relevant design parameters and quantities to each other.
Calculations	Solved equations (i.e. with values) used to show how input parameters and results were calculated.
Flow Charts	Images organizing a design process, decision, or chain of reasoning into a step-by-step chart.

The same seven projects were then reviewed again by the two researchers. They held an additional round of negotiation in the coding process and identified that students often did not follow the proposed nomenclature for each step of the modeling process. For example, some students used the heading “configuration of the model” to describe what in fact was the validation of the model. It was also found that students sometimes put multiple representations together in one single figure. Researchers agreed that, despite the eventual students’ misconceptions about modeling and simulation steps, the analysis should categorize the representations based on how the students were using them to explain information according to the rubric definitions for each step, rather than how the students organized them in their papers. Regarding the number of representations within a single figure, the researchers agreed on characterizing and counting them as multiple representations instead of a single one if students included comparative discussion of each representation in the figure. Figures containing multiple representations that were not differentiated by the student were counted as a single instance of the representation. Once these agreements were reached, one of the researchers completed the coding process for the remaining 80 percent of the project submissions.

The second step in the analysis consisted of comparing three data sources within each step of the modeling and simulation process: (1) the students’ representations (i.e., number and type); (2) student score according to the rubric criteria; and (3) the instructor’s comments on the student modeling and simulation processes. While the first two sources were numerical or categorical (e.g., the type of representations) data, the instructor’s comments were in textual format, which required additional categorical analysis. This qualitative analysis process was carried out within each of the steps, in order to identify common effective and ineffective strategies carried out by the students. To investigate the relations between the uses of the different types of representations, we computed the correlation between number of representations per stage and students' respective score. After that, we conducted multiple linear regressions to evaluate the relationship between the use of different representations and students' score.

Results

This study explores the student modeling and simulation process and the use of external representations within each of these steps. This section is organized based on the five steps of which students needed to complete and present evidence: (a) problem framing, (b) model configuration, (c) validation of the model, (d) discussion of the solution, and (f) conclusions and recommendations. Within each section, we present the type and number of external representations that students generated. We also present a comparison between the low performing and high performing students, divided in such categories according to the overall performance on the project. Students were split into two groups for the analysis: high performers and low performers. Students who scored higher than a 70 on the project were classified as high performers (n=25), while students who received a 70 or below were classified as low performers (n=10). At the end of each modeling and simulation step, we also include samples of the course instructor's comments that provide in-depth understanding of good and poor strategies students used towards the overall project goal.

Problem Framing Step

In this step, students were expected to determine the project's objective and identify its challenges. In addition, students performed a literature review to contextualize the problem and investigate the properties of their design. On average, high performers tended to use more images and plots in their framing section than low performers. The inclusion of tables for organizing data and key variables was more common among high performers, but by a smaller margin than plots and images. Equation use also saw increased use from high performers, but tended to be used less than other forms of representations in both groups. Calculations and flow charts saw almost no use from students in both groups, with only one instance of each from the high performing group and none from the low performance group. Figure 1 depicts the types and average number of representations used during the problem framing step summarized for high and low performers.

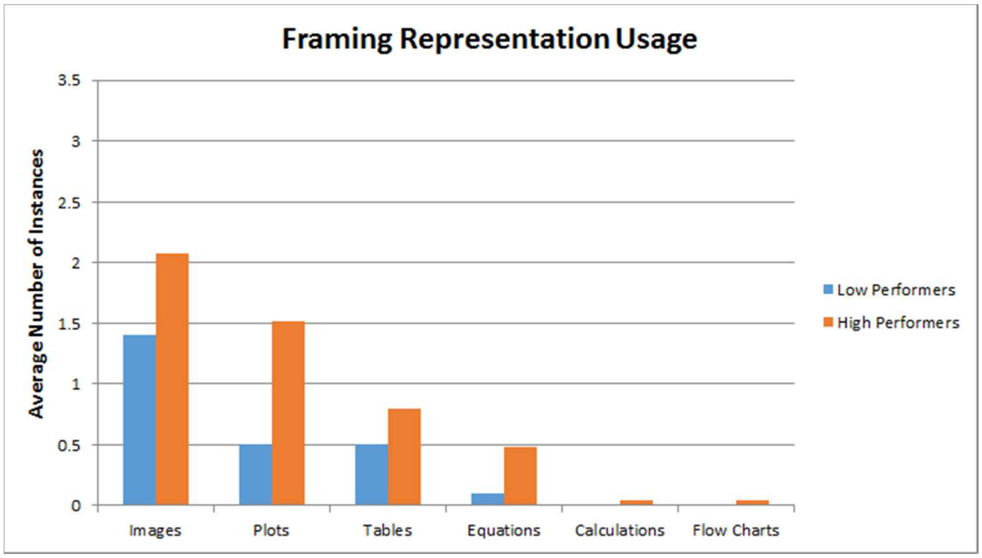

Figure 1. Types and average number of representation usage in the problem framing step between high and low performers

The common theme from the course instructor's comments among students with low scores for the framing section is that their literature review is disconnected from the rest of the report. Conversely, high performers completed a thorough review of literature, making clear connections to their own project. Table 2 presents some sample comments written by the instructor.

Table 2. Selected grader comments on framing sections.

Level of performance	Comment
Full credit	*"Very nice review and connection between mechanics of a wireless drill and power requirements."*
Partial credit	*"Literature review does not lead to parameter selection. Seems disconnected from rest of document."*
	"Introduction of materials to be used was superficial. Some of the statements made were not supported."

Configure the Model Step

In this step, students performed a preliminary analysis that would help them solve the design problem. Activities expected as part of the analysis included defining goals, information, assumptions, and boundary conditions in terms of relevant concepts, theories, or models used in class or found in the literature. It also included identifying the parameters of the model, as well as assumptions and limitations. Figure 2 shows the types and average number of representations used during the model configuration step summarized for high and low performers. In contrast with the framing section, students primarily used equations and calculations to explain their model in the configuration step. As with the project framing, students with lower overall project scores show less representation use across the board. Equation use is closer between the two groups, but calculations (i.e. "showing their work") are used noticeably less by students with lower scores.

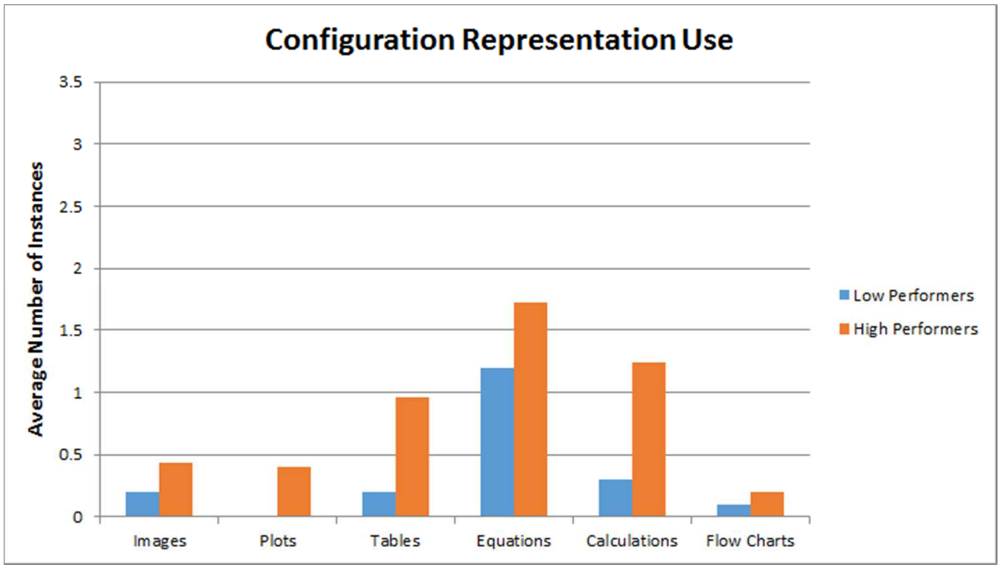

Figure 2. Types and average number of representation usage in the model configuration step between high and low performers

Common themes among students with lower scores in the configuration section were poor or unclear justification of parameter selection or the selection of materials contrary to the information provided in the literature review. Students with higher scores tended to make clear mathematical connections and justified their parameter selections using concepts from the course material. Table 3 presents comparative comments provided by the instructor.

Table 3. Selected grader comments on configuration sections.

Level of performance	Comment
Full credit	*"Model presented utilizes parameters and concepts developed throughout the semester. It builds up the different levels of losses until it arrives to the Newman model. Design approach is abstracted into a flow chart."*
Partial credit	*"Equations, assumptions, and narrative of model/design were vague at best. Justification of parameters were physically confusing."*
	"Selection of material and device parameters is there but justification is completely absent."

Validate the Model Step

In order to validate the model, students were expected to determine whether the analysis/design satisfied the problem's requirements. Students validated their solutions by testing simple scenarios, by developing "toy" models (e.g., using a python or MATLAB code of a simple test case, or comparing it against existing designs), by means of simulating the experimental conditions under the same assumptions, or by means of test cases using another analytical tool. Figure 3 depicts the types and average number of representations used during the model validation step summarized for high and low performers.

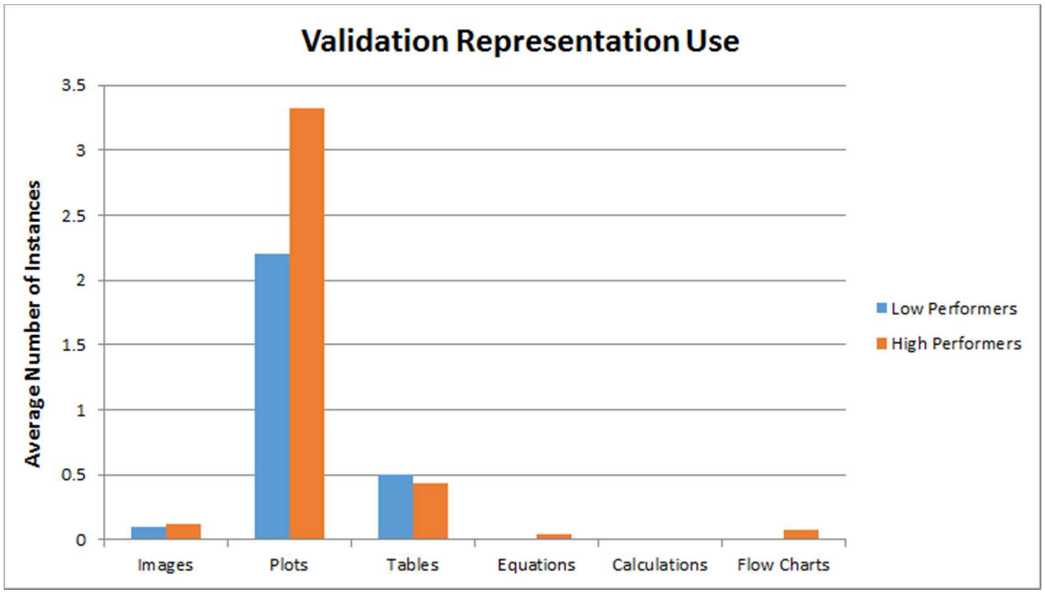

Figure 3. Types and average number of representation usage in the model validation step between high and low performers

Common themes among students with lower scores included poor justification of the included plots, unclear explanation of simulation details, and lacking or missing discussion of physical/practical interpretations. High scoring students tended to make strong connections between their chosen parameters and their simulation results, as well as clear discussion of what their resulting data means in terms of the physical design of the battery. Table 4 depicts sample comments provided by the instructor.

Table 4. Selected grader comments on validation sections.

Level of performance	Comment
Full credit	*"Proposed design nicely flows from DualFoil calculations and concluded parameters are then compared against practical aspects."*
Partial credit	*“Parametric analysis is only stated in terms of the attached figures. Conditions such as depletion and diffusion limitations are never highlighted.”*
	"Justification and discussion of design is lacking. Narrative focuses on description of figures without any physical interpretation."
No credit	*“Reported trends are in contradiction with what is observed and does not support design.”*

Discuss the Model Step

As part of the discussion, students examined the results to determine if their solution made physical sense and specified operational ranges for the design (i.e. identifying where it would stop working). Students were also expected to identify any limitations in their design. In this step, the use of data from industry or data published in scientific papers was particularly encouraged. Figure 4 shows the types and average number of representations used during the problem discussion step plotted for high and low performers.

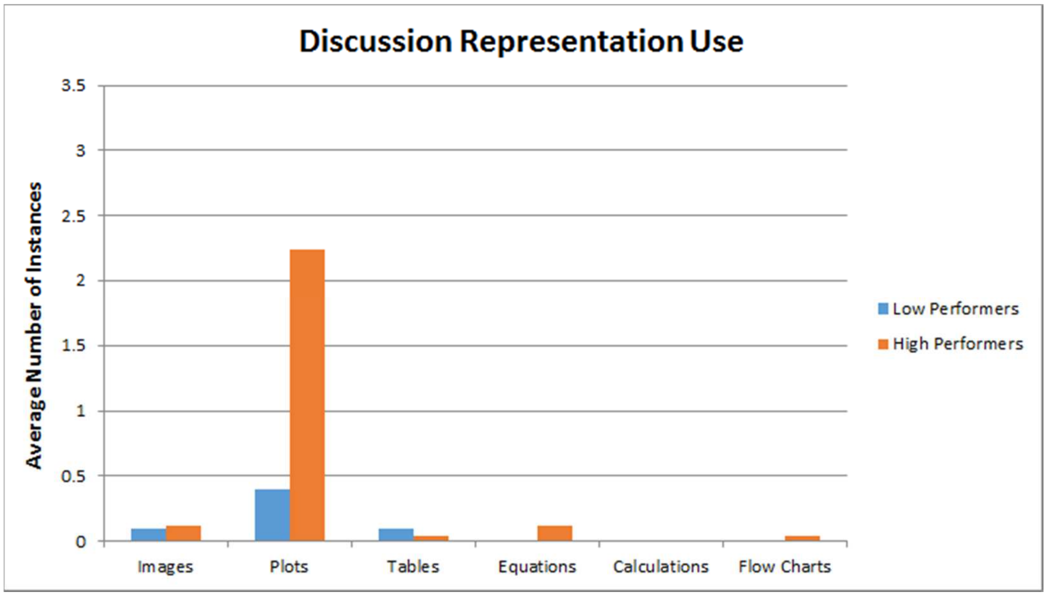

Figure 4. Types and average number of representation usage in the model discussion step between high and low performers

Similar to the validation step, plots were also the dominant representation type in the discussion step. However, students with lower scores showed a much lower utilization of plots than their higher-scoring counterparts when compared to the difference from the validation step. On average, lower scoring students used approximately two fewer plots than higher scoring students, as opposed to the one fewer plot of the validation step. Other types of representations were rarely used in the discussion by students of either group.

Students with lower scores in the discussion section tended to include only superficial descriptions of the included figures with little to no interpretation with respect to their model, or the discussion of their results was simply missing from the paper. Higher scoring students tended to include extra analysis of the results to contextualize their findings and determine whether or not their design offers a physically reasonable solution to the problem. Table 5 below shows sample comments from the instructor for students who were awarded full credit, partial credit, and no credit.

Table 5. Selected grader comments on discussion sections.

Level of performance	Comment
Full credit	*"Discussion on side reactions demonstrates that used numbers are unphysical. Justification of the rest of parameters is very good."*
Partial credit	*“Parametric analysis is missing. Discussion of design does not follow, nor is consistent with what is stated in page 2.”*
No credit	*“In general, discussion is simply a description of the figures without any scientific explanation of the results. Needs to review concepts and correlate them to results.”*

Conclusions and Recommendations Step

In this section, students were expected to show and explain their solution, including all the utilized parameters. Students were asked to interpret the output of their solution and show how the proposed solution addressed the problem. Students were also expected to demonstrate if the battery works and to provide the parameters and operational ranges for which it will work, as well as to discuss if their battery design is practical (or even possible) given the constraints of their application. If the design did not solve the initial problem, students were asked to provide an explanation or justification for why that particular design might not work, as well as suggestions for how it could be improved. Figure 5 depicts the types and average number of representations used during the conclusion step summarized for high and low performers. A low average number of external representations were used in this step of the modeling process. Tables, plots, and images were used primarily to organize the results of the project, rather than to provide new or further insight into the solution.

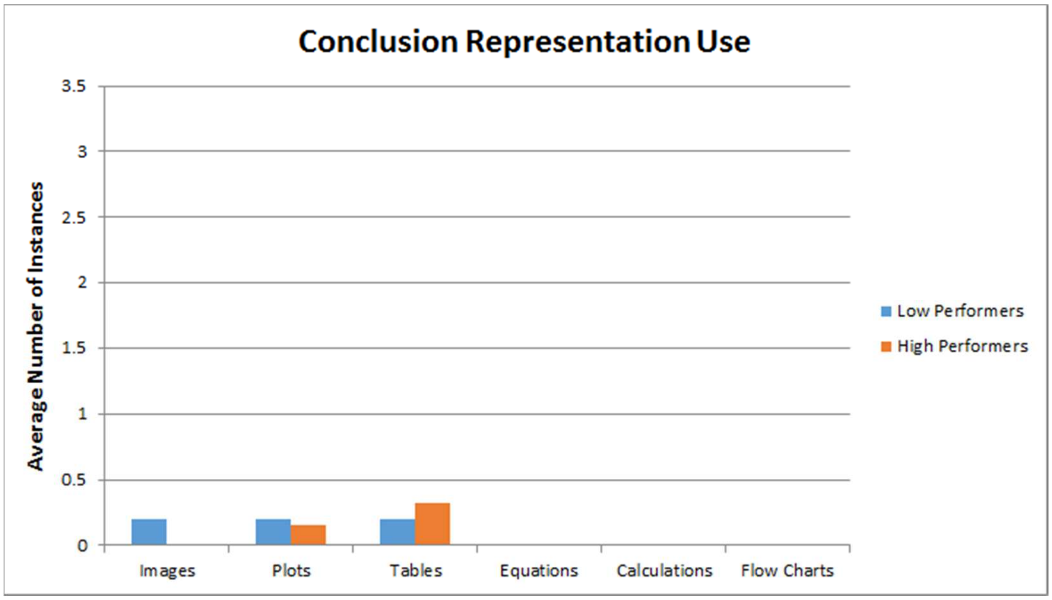

Figure 5. Types and average number of representation usage in the problem solution and discussion step between high and low performers

Students with lower scores in the conclusion step either did not include the conclusion section in their report or provided conclusions that were superficial (i.e. students simply described the solution without any discussion of limitations or potential improvements). Lower scoring students were also commonly docked points for providing conclusions/solutions that contradicted other portions of their analysis or parameterization. Higher scoring students included strong summaries of their work that showed agreement with their analysis, often including limitations and potential for future work. Table 6 shows samples of instructor's comments to students provided for cases for full and partial credit.

Table 6. Selected grader comments on conclusion/solution sections.

Level of performance	Comment
Full credit	*"Conclusion makes a good point as to the limitations of these constraints and points toward what would help have a better design."*
Partial credit	*"Conclusion was reasonable but not supported by document/analysis."*
	"Conclusions are unrelated to analysis. Contradicts results."

Relationship between Students' use of Representations and Overall Performance

The final step in the analysis consisted of a statistical analysis of the numerical data. In general, there was a weak Pearson correlation coefficient (below .3) between students' use of representations in each stage and the respective scores. One exception was the configuration step, where the score was well correlated with the amount of representations used. The correlation resulted in a value of .52 (p-value = .002) for the configuration step. To evaluate the effects of each type of representation on this score, we performed a multiple linear regression. Equation (1) describes the model used to predict students' score on the configuration step (SC) based on the numbers of images, plots, tables, equations, calculations, and charts. Results reveal a significant effect of the use of equations on this stage (p-value < 0.016). No other type of representation had significant effect. This fact could reflect the importance of the use of equations to students' understanding of the different phenomena associated with the problem. Furthermore, these equations allow the definition of several parameters that affect battery performance and are essential in the configuration stage.

$$SC \sim Images + Plots + Tables + Equations + Calculations + Charts \tag{1}$$

A simple linear regression was calculated to predict students' final scores (SFS) based on the total number of representations per student (Rep). Equation (2) describes the regression model.

$$SFS \sim Rep \tag{2}$$

Results reveal a significant effect of the use of representations on the final score ($F(1, 32) = 14.29$, p-value < 0.01), with an adjusted R^2 of 0.287. Although it was an expected result, this significant finding points toward the importance of representations, not only as a tool for fostering engineering learning, but also as a way to better express engineering ideas, concepts, and designs.

Discussion

How do students use external representations in each step of the modeling and simulation process?

The use of external representations proved to be an effective strategy to support the modeling process across all of the steps. The framing stage showed the largest average use of images, suggesting that this is an important type of representation for understanding the problem and connecting it to existing literature. The configuring stage presented the widest variation in the use of representations, including images, plots, tables, equations, calculations, and flow charts.

Of the six steps of the modeling process, the validation step saw by far the highest use of plot-style representations, followed by the discussion phase. These two steps involved the interpretation of results from the computational model. Hence, it is expected that their external representations focus on data generated from these models. Finally, representation use in the conclusion section was uniformly low for all students, with most students opting to simply summarize their project solution in words.

How do students' implementations of the modeling and simulation process relate to the quality of their battery system design?

Overall, students with higher quality battery system designs followed all of the steps from the modeling process, making clear connections among them and using more external representations (on average) to justify their decisions. Some interesting patterns within the type of external representations for each step can be identified. For example, high performers used significantly more plots when framing their material, possibly suggesting a stronger connection between project concepts and the data supporting those concepts. The inclusion of tables for organizing data and key variables was more common among high performers, but by a smaller margin than plots and images.

During the configuration step, high performers used more calculations than low performers. This type of external representation might have helped these students to contextualize the mathematical equations to specific cases within their projects, possibly facilitating increased organization in their justifications of parameter selection. Students with both high and low scores in the validation step used considerably more plots to help justify their solutions. As with the other steps, however, students with lower overall scores still tended to use fewer plots in their validations, at an average of one fewer plots per section than high scoring students.

Similar to findings from other studies[24], our results suggest that students who scored at the population median or higher were more likely to integrate more representational forms and strategies in communicating their solution to the different stages of the modeling and simulation process. We hypothesize that students who created more representations benefited from the process by acquiring a better understanding of the problem and by using them as tools with which to think [16]. Chi, Feltovich and Glaser [25] have argued that when learners represent a problem, the emphasis is usually placed in the abstraction of information process as the key component in guiding the construction of a solution. In addition, this abstraction process has also been shown to help experts identify the associated information and interactions from a knowledge domain needed to solve a particular type of problem [25].

We also hypothesize that low performers may have experienced difficulties in creating useful representations and benefiting from them due to a lack of the required previous knowledge [26], or because of difficulties in applying or mapping knowledge about graphical representations while simultaneously comprehending new domain knowledge [13,21].

Conclusion, Implications and Future Work

The implications of this study relate to helping students develop beyond the approach of simply using representations to convey concepts and into a more complex approach in which students are able to systematically develop and use representations to express their ideas and intentions. These two approaches can be described as representational competence[27] and representational fluency[28], respectively. While representational competence refers to the ability to express, use, and think about representations[27], representational fluency goes beyond creating and using representations into engaging students in practices of mapping and translating both between and within different representations[29]. Future work is needed to identify how to effectively foster these representational skills at the undergraduate level. Deeper investigations in this area can result in the development of learning materials, scaffolding methods, and pedagogical approaches that can guide the design and integration of expert practices and computational tools into undergraduate curricula.

This study is relevant because the use of external representations has been identified as central to the practices of engineering. Specifically, this study identifies preliminary work concerning how external representations and representational processes are used as part of the modeling and simulation process, allowing individuals to gain insight into the material world by representing it through diagrams, graphs, equations, computer simulations, and so on. This study lays a foundation for future research of graphical representations in engineering and provides in-depth details describing how learners use multiple forms of representations and tools during the modeling and simulation process.

Potential limitations of this study arise from only having one person (the course instructor) scoring the projects. However, we have worked intensively with the course instructor to develop measures to account for this possible threat. The grading rubric (detailed in the appendix) provides the course instructor with specific criteria as guidance for scoring the projects. This rubric and the scoring process have been iteratively refined during the last three years, minimizing the risk of instructor bias in the grading of the reports.

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Appendix

Grading Rubric	
Problem Description (20%)	Determine the project's objective and identify its challenges.
Problem Framing (30%)	Conduct a literature review to contextualize your problem and investigate the properties of your design.
Configure the Design/Model (20%)	Perform an analysis (e.g., define the parameters of the model) that will help you solve the design problem (define goals, information, assumptions, boundary condition, etc.) in terms of relevant concepts, theories, or models used in class or from the literature. Identify assumptions and limitations.
Validate the Model (15%)	Establish whether the analysis/design satisfies the problem's requirements. You can validate it by testing simple scenarios, by developing your own "toy" model (e.g., a python or MATLAB code of a simple test case, comparing it against existing designs, etc.), by means of simulating the experimental conditions under the same assumptions, or by means of test cases using another analytical tool.
Discuss the Design/Model (15%)	Examine the results to determine if the solution makes physical sense and specify operational ranges from where the design will stop working: identify limitations along with ranges of operation. The use of data from industry, or data published in scientific papers is encouraged.
Solution and Conclusion (20%)	Show and explain your solution, including all the utilized parameters. Interpret the output and show how the proposed solution addressed the problem/project. Demonstrate if the battery works, the parameters in which it will work, or if it is impossible to produce a battery like that based on the parameters. Identify an explanation/justification of why that doesn't work.