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Cultivating creative thinking in engineering student teams: Can a computer-mediated virtual laboratory help?

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Abstract

In engineering design, engineers must be able to think creatively, effectively toggling between divergent thinking (developing multiple novel ideas) and convergent thinking (pursuing an appropriate idea using engineering analyses). However, creative thinking is not emphasized in many undergraduate engineering programs. In this empirical study, we analyze the divergent thinking of teams working on a virtual laboratory project. Fifteen student teams' solution paths–as represented by Model Maps–were analyzed to characterize and compare the various elements of divergent thinking: fluency, flexibility, and originality. The solution paths of these teams were compared in two physical laboratory projects and to experts completing the same virtual laboratory project. We found that students demonstrated more divergent thinking in the virtual laboratory project than in the physical laboratory projects; yet, divergent thinking and quality of solution did not correlate. There was little difference between measured elements of divergent thinking between student teams and experts.

KEYWORDS

design based research, problem-based learning, skills, sociocultural, undergraduate, virtual/3D environments

1 | INTRODUCTION

1.1 | Overview

This article characterizes how a learning environment where data are collected using a computer-simulated virtual laboratory can engage engineering students in creative thinking. Creativity, or "the ability to develop something innovative and useful from pre-existing knowledge" (Liu & Schonwetter, 2004), is a necessary skill for engineers to develop new products and processes (Steinwart & Ziegler, 2014), stimulate industrial change and economic growth (Badran, 2007), and solve new and challenging problems (Runco & Acar, 2012).

This design-based research study investigates student solutions to laboratory-based design projects meant to reflect real engineering work. Specifically, in a within-subjects design, we compare ways creativity is expressed in student teams' solutions for a computer-based authentic task to two physical laboratory projects. In addition, we compare their elements of creativity to that of a team of experts. The computer-based task provides an open-ended environment without the time and safety constraints associated with a traditional physical laboratory. Consequently, the teams are afforded opportunity to be more creative than they might typically be in a physical laboratory project, toggling between divergent thinking, to generate multiple ways to optimize the process, and convergent thinking, to decide and enact the best solution approach. With an understanding of how students employ divergent thinking in this authentic virtual environment, instructors can better employ computer-assisted learning to equip students for professional practice.

1.2 | Creativity in in engineering practice and engineering school

Creativity is often considered an essential aspect of engineering practice (Clough, 2004). As problems become more complex and wide-reaching, creativity becomes more essential; it would not be possible for engineers to address change–in population, climate, security, economics, and technology–without creative solutions (Cropley, 2015). Broadly, creativity can be defined as the "production of ideas that are both novel and useful or appropriate" (Sternberg & Lubart, 1995); in engineering, the "useful or appropriate" part is particularly important, as an original or unique solution means nothing if it is not functional or does not meet desired specifications (Shah, Cargas-Gernandez, & Smith, 2009). Creativity is often associated with constructs like inventive thinking (DeHaan, 2009), creative problem solving (Treffinger & Isaksen, 2005), innovation, or entrepreneurship (Chang, 2016; Weilerstein & Byers, 2016).

Despite the need for engineers to be creative, curricula often do not sufficiently attend to the development of creativity in engineering (Chen, Tao, & Zhou, 2018). Core engineering science courses that comprise the majority of the undergraduate engineering curriculum include closed-ended problems with one right answer and algorithmic solution paths that do not emphasize or value creative thinking (Felder, 1987). At the same time, it is not yet clear how creativity can be taught or assessed in engineering (Baillie, 2002; Griffiths, 2008). Students are also influenced by the perceived value of creativity of their instructors (Tolbert & Daly, 2013). Although engineering faculty report that they value creativity (Kazerounian & Foley, 2007), if they do not discuss or reward creative thinking, students do not believe that creativity is a core element of engineering work (Badran, 2007; Carpenter, 2016). In fact, several researchers report that engineering education programs *decrease* creativity in students (Hadgraft, 1997; Kim, 2011; Wilde, 1993; Zappe et al., 2015). Consequently, there remains a concern that undergraduate engineering programs are not doing enough to encourage creativity (National Academy of Engineering, 2004; Rugarcia, Felder, Woods, & Stice, 2000; Sheppard, Macatangay, Colby, & Sullivan, 2009).

Recently, educators have identified innovative teaching techniques in engineering courses to better teach creativity (Daly, Mosyjowski, & Seifert, 2014; Liu & Schonwetter, 2004; Zhou, 2012). Zhou identified three teaching methods that encourage creativity in engineering students: building learning environments that support creativity, doing open-ended problem-solving, and using tools that encourage creative thinking (Zhou, 2012). Authentic engineering tasks like design problems or open-ended laboratory projects allow students to practice and develop creative thinking skills in ways that align with Zhou's recommendations (Prince & Felder, 2006). In these tasks, there is not typically one right answer, and students must collaborate and cooperate in their groups as they draw on and apply a variety of knowledge to come up with an appropriate solution (Johnson, Johnson, & Smith, 1998).

One limitation to increasing the frequency in which students engage in this type of instruction are the practical constraints of large enrollment university programs. Working in a physical laboratory with real materials and equipment can be time, resource, and labor intensive (National Research Council, 2011). Virtual laboratories–computer simulations based on mathematical models that provide values of output variables in response to user-selected input variables–provide a practical alternative to address these constraints (Potkonjak et al., 2016) by providing students access to environments, contexts, or problems that are not found in a typical college laboratory (Abulrub, Attridge, & Williams, 2011; Koretsky, Amatore, Barnes, & Kimura, 2008). Systematic comparisons of virtual and physical laboratories have mostly focused on development of conceptual understanding (de Jong, Linn, & Zacharia, 2013). However, research on the ways that virtual laboratories compare to physical laboratories in developing students' creativity is sparse.

2 | THEORETICAL FRAMEWORK

2.1 | Divergent and convergent thinking

One common conception of engineering creativity is that it must encompass both divergent thinking (generating novel ideas) and convergent thinking (evaluating and executing the novel ideas) (Cropley, 2006; Liu & Schonwetter, 2004). Engineering creativity is not only about the variety or number of ideas created; the chosen solution must also be functional and applicable (Charyton & Merrill, 2009; Cropley, 2006; Dym, Agogino, & Eris, 2005; Liu & Schonwetter, 2004). Building on this literature, our definition is as follows: creative thinking in engineering is the toggling between divergent thinking and convergent thinking to create a desired solution to an engineering problem (Cropley, 2015; Cross, 2004; Daly et al., 2014; Liu & Schonwetter, 2004).

The ideas of divergent and convergent thinking stem from Guilford's (1956) structure of intellect, which encompasses cognition, memory, evaluation, divergent thinking, and convergent thinking. Divergent thinking is considered to be the cognitive basis for creativity. It involves generating multiple ideas for a possible solution and is considered to be a critical skill in generating "good ideas." In order to solve a novel problem, engineers often must think of multiple potential solution paths before they can identify the path that will work well (Runco & Acar, 2012). Divergent thinking encompasses fluency (generating many ideas), flexibility (generating a diverse set of ideas), originality (generating unique or novel ideas) and elaboration (expanding upon an idea) (Hsiao, 2014; Liu & Schonwetter, 2004).

Meanwhile, convergent thinking utilizes critical thinking (Ahern, Connor, McRuairc, McNamara, & Donnell, 2012) and is considered to be "digging deeper into ideas" (Treffinger, Young, Selby, & Shepardson, 2002). It involves analyzing and evaluating generated ideas to select an appropriate solution path that fits within given constraints (Brophy, 2006; Cropley, 2006; Daly et al., 2014; Liu & Schonwetter, 2004), which for engineers often involves procedurally completing calculations or experiments according to engineering norms. Studies of engineering students have found that their use of divergent thinking is often disconnected from their use of convergent thinking. When comprised of diverse students, teams often abandon the ideas generated divergently, in favor of following a more traditional or common solution path (Starkey, Toh, & Miller, 2016).

By engaging in open-ended tasks that require divergent thinking, engineers are able to develop knowledge and skills that support them in finding successful solutions (Christiaans & Venselaar, 2005). Such knowledge includes both domain-specific principles and procedures and more general knowledge about the design process itself. In complex tasks, practicing engineers often toggle between divergent thinking and convergent thinking to come to a final solution (Cross, 2004; Dym et al., 2005). Rather than simply generating a set of ideas and then selecting the most attractive path, expert engineers iterate between multiple paths and solutions while solving engineering design problems (Atman et al., 2007). However, there is still little understanding of *how* engineers toggle between these two types of thinking. As a first step, in this study we seek to characterize the elements of divergent thinking of engineering teams doing realistic projects.

2.2 | Group creativity

Just as one can consider how an individual is creative, group creativity can also be studied to see how several individuals coordinate their ideas while working together. Indeed, some scholars argue the group forms the fundamental unit of creativity (Glaveanu et al., 2019). Often group creativity exceeds the sum of the individual creativity of each team member; it is also developed and encouraged differently than individual creativity (Mumford, Feldman, Hein, & Nagro, 2001). Divergent thinking can be more successful for a group than for individuals, as group interactions stimulate the generation and consideration of ideas from multiple perspectives; convergent thinking can also improve, as teams debate and evaluate ideas more deeply (Levine & Moreland, 2004; Usher & Barak, 2020; Zhou, Kolmos, & Nielsen, 2012). Jordan and Babrow (2013) specifically identify engineering design tasks as activities in which group communication is vital to negotiating uncertainty and developing creative solutions. In this work, our unit of analysis is the group, as we are broadly interested in how students can be creative by working together in these ways.

3 | STUDY DESIGN

The reported study sits within a larger research program to understand how computer-mediated authentic, ill-structured engineering projects enable the broad professional development of engineering students (Koretsky, Kelly, & Gummer, 2011; Koretsky, Vauras, Jones, Iiskala, & Volet, 2019; Sherrett, Nefcy, Gummer, & Koretsky, 2013). The program is based on a theoretical framework of design-based research (DBR) in education. In DBR, innovative educational systems are deployed in naturalistic settings; simultaneously experiments studying the innovative systems are systematically conducted (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003). Brown (1992) and Collins (1992) argue that DBR is particularly appropriate for studies of learning in complex systems mediated by technology tools, such as the Virtual Chemical Vapor Deposition (VCVD) project studied here.

In the VCVD project, student teams must address an open-ended, "real world" task: creating computer chips using a chemical vapor deposition process (Koretsky et al., 2008). Since teams collect data virtually using a computer, they are able to complete an industrially-relevant task that would not be able to be done otherwise within the context of an undergraduate laboratory course due to constraints with time, space, budget, and expertise. The learning system was not designed as an intervention specifically targeting creativity, but rather as a realistic engineering project where creativity is among the needed skills to make progress. Past research focused on this virtual laboratory has demonstrated that students show enhanced awareness of experimental design and greater references to critical thinking and higher order cognition in this context than in physical laboratories (Koretsky et al., 2011). However, it had not yet been studied–in this environment or another virtual laboratory environment–how students practice creative thinking, for example, how their creative thinking compares to that in the physical laboratory projects or to that of experts. This study specifically seeks to characterize the elements of teams' divergent thinking in this context.

We take a sociocultural perspective of learning (Cole, 1996; Greeno, 1998) that shifts the focus from the behavior, skills or mental structures that students acquire to the meaningful ways they participate in the practices of engineering (Lave & Wenger, 1991). Correspondingly, rather than using post-activity tests to assess gains in creative thinking (Charyton & Merrill, 2009; Kim, 2006; Torrance, 1972), our research design seeks to characterize the elements of creative thinking from the artifacts produced during the work itself. While we acknowledge that this approach does not allow us to directly "see" the creative thinking, such analysis provides a connection between the characteristics of an activity and the types of thinking it elicits.

In a within-subjects design, we compare elements of divergent thinking of teams completing the VCVD project to two physical laboratory projects within the same course. We then compare the divergent thinking of student teams to that of experts who completed the VCVD project as a measure of validity. Throughout the laboratory course, participants maintained a laboratory notebook. The notebooks were analyzed in order to create Model Maps (Sherrett et al., 2013), which illustrate how students conceptualize the problems they are approaching and the solution strategies that they ultimately employ. The Model Maps were analyzed within a framework of creative thinking to characterize elements of divergent thinking in the teams' solution paths.

The following research questions guided the research:

1. How do teams employ divergent thinking in the virtual laboratory project, as shown in the Model Maps?
2. What is the relationship between divergent thinking and solution quality in the virtual laboratory project?
3. How do student teams' divergent thinking characteristics compare between virtual and physical laboratory projects?

4. How do divergent thinking characteristics compare between experts and student teams in the virtual laboratory project?
5. How do students perceive the open-endedness of the virtual laboratory project in comparison to physical laboratories and homework? How do students and experts compare the open-endedness of the VCVD project to the real work they have done in industry?

4 | METHODS

4.1 | Participants and setting

This study was situated within the context of a senior laboratory course in a Chemical, Biological, and Environmental Engineering program in a public university located in the Pacific Northwest of the United States. All students in the program were required to take the course in their final year of study. This study focuses on the work of fifteen teams; students self-selected into three-person teams and remained in the same team throughout the quarter. This study also considers the work of three expert completions of the VCVD project. The experts were engineers with multiple years of industrial experience and were selected to provide variation in disciplinary background and experience: one was a team of mechanical engineers, one was a team of chemical engineers, and one was an individual chemical engineer. The team of chemical engineers had industrial experience with processes similar to CVD and but the team of mechanical engineers and the individual chemical engineer did not. The first author is an engineering education researcher who participated in ethnographic research, but not the course instruction. The second author conceived of the learning system design and leads the DBR research program. This study received approval from the Institutional Review Board and all participants provided written consent.

4.1.1 | Laboratory design projects

As part of the course, students participated in three laboratory projects, each lasting three weeks. All projects were framed to situate the teams as performing an industrial project tasked with delivering a design recommendation. The project assignments were presented as memoranda from the parent company with the instructor acting as the team's supervisor. To develop their design recommendation, teams needed to perform experiments and interpret the data they collected.

In the first two projects, students collected data in physical laboratories (PL1 and PL2). The third project was the VCVD project. The first physical laboratory project (PL1) had student teams design a process to pre-heat potable water by recovering energy from a waste steam using an available heat exchanger. The second physical laboratory project (PL2) had student teams design a process to reduce calcium content in a waste process stream using an available ion exchange column. In each of these projects, the teams used data collected on bench-scale equipment to make a recommendation for a larger industrial scale process.

The virtual laboratory project (VCVD) had teams develop a "recipe" for one step in the manufacture of computer chips. They needed to optimize a set of chemical vapor deposition reactors to achieve a target thickness of silicon nitride with high reactant utilization, high uniformity, and low process time–though the trade-off between these competing constraints was not specified. Teams were charged virtual money for each experimental run and each measurement. They were expected to design a set of experiments in order to determine an appropriate set of reactor parameters; run the experiments; analyze the data to determine next steps; and iterate on these steps until they sufficiently satisfied the engineering objectives while keeping budget in mind. Output data were generated by a rigorous numerical simulation to which random and systematic process and measurement error were added. Screenshots of the student interface are shown in Figure 1. While teams collected data through this interface, they completed their other project work through face-to-face collaboration. With the virtual environment, students could complete experiments quickly and outside of scheduled laboratory times, so that during class, students met with the project supervisor (instructor) in structured weekly meetings. In the final laboratory period, each team delivered a 15-minute oral presentation to their peers and several faculty followed by a 15-minute question and answer session.

More details including the design principles for the virtual laboratory project are reported elsewhere (Koretsky et al., 2008).

4.2 | Data collection

4.2.1 | Laboratory notebooks

The primary data source used in this work is the student team's laboratory notebook that they used throughout each of the three laboratory projects in the class. A sample page of a laboratory notebook from the first experimental run in the VCVD project is shown in Appendix A (Figure A1). At the start of the course, teams were provided feedback on keeping detailed notebooks. Notebooks were graded at two-week intervals based on level of detail included, but not on the particular approaches taken. By the completion of the three projects, notebooks typically contained 50–100 pages of the team's inscriptions. Other data sources included course deliverables associated with the projects, which consisted of individual written reports in the physical laboratories and a team written and oral report in the virtual laboratory. The laboratory notebooks served as the primary artifact for this study because they show the approach that teams took toward developing a solution; if documented properly, the notebooks demonstrated all of the solution pathways that students considered (divergent thinking) and how they narrowed down their ideas to land on one pathway they took (convergent thinking).

The experts only completed the VCVD project. Like the student teams, they recorded their activity in a laboratory notebook. The experts were not required to complete final written and oral reports, although one of the expert teams did voluntarily present their recommendation in an oral report.

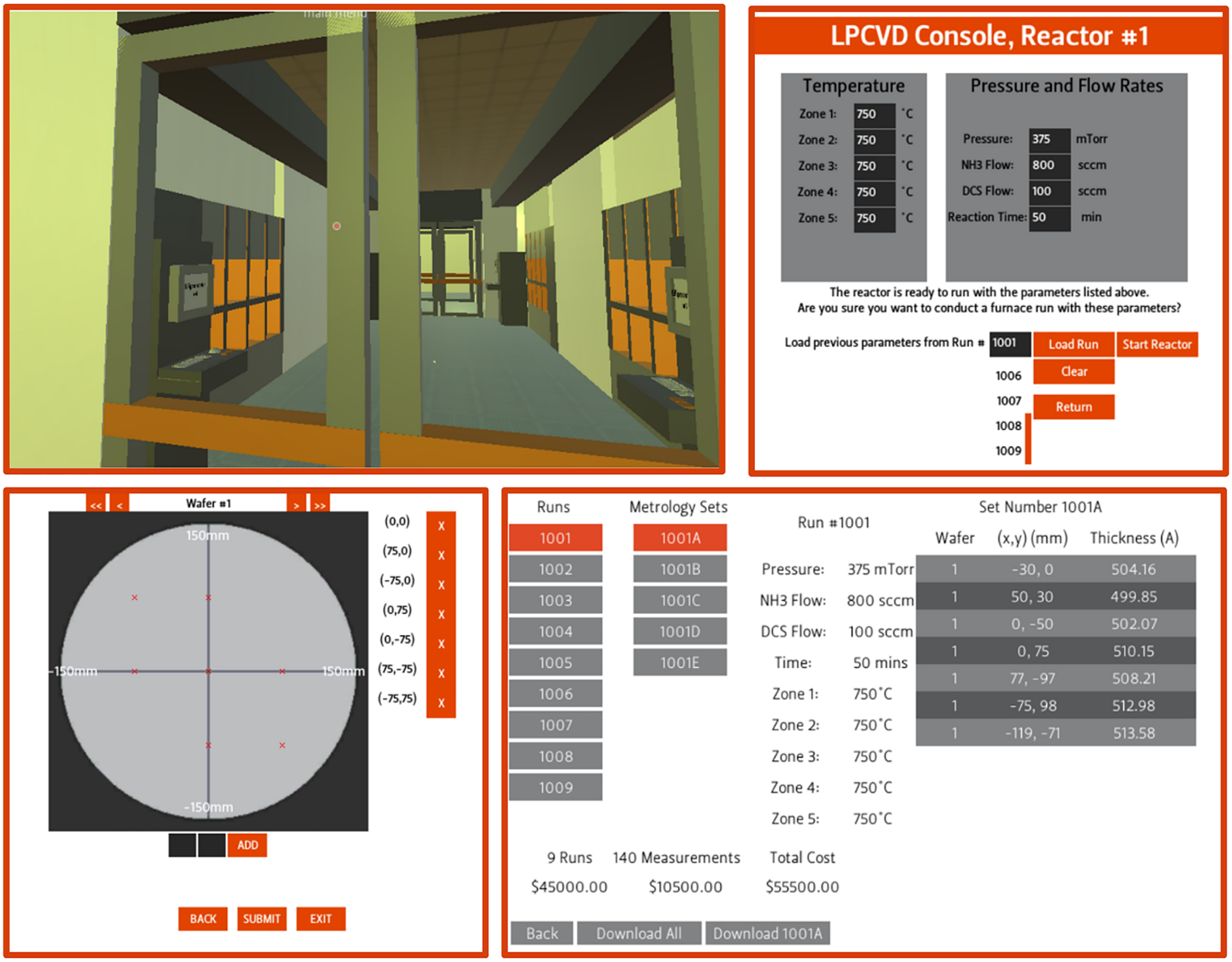

FIGURE 1 Screen shots of the VCVD laboratory showing the bay and chase layout of the wafer fabrication facility (top left), reactor parameter input screen (top right), part of the measurement interface (bottom left), and data summary window (bottom right) [Colour figure can be viewed at wileyonlinelibrary.com]

In the VCVD project, all participants attended two meetings with the course instructor: a Design Meeting one week into the project to discuss their strategy and gain approval to run the reactor, and an Update Meeting two weeks into the project. These two meetings were recorded and later transcribed and were utilized in creating the Model Maps.

4.2.2 | Post-project interviews

As a secondary data source, we analyzed interviews with four experts and nine students who were selected since they participated in a companion ethnographic study. In that study, select teams were audio-recorded any time two or more members met while a researcher took field notes, and interviewed after the VCVD project was completed (Gilbuena, Sherrett, Gummer, Champagne, & Koretsky, 2015). The portion of the interview analyzed in this study related to project open-endedness as we sought to explore the conjecture that a more open-ended project would elicit more elements of divergent thinking. Students were provided a scale labeled “constrained” on the left side and 'open-ended' on the right side and asked to place four types of activities on the open-endedness scale: typical homework, physical laboratory projects, the virtual CVD laboratory project, and internship projects (one example is shown in Figure 2). Participants wrote their responses on paper and were asked to talk through their reasoning for activity placement. In some cases, they also wrote part of their reasoning. The interviewer then asked follow-up questions about the placement (e.g., What differences are there in your approach to a problem, based on where it falls on that spectrum? If you look at the spectrum, can you talk about your comfort level along it, what types of problems are you most comfortable or least comfortable with? But also maybe your preference level?). The experts were asked how the simulated virtual laboratory project compared to the experiences as professionals.

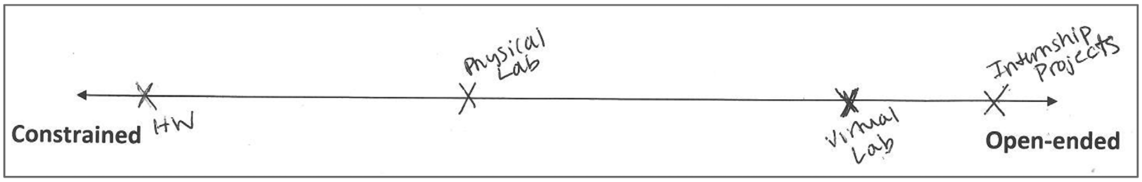

FIGURE 2 Example student response to open-endedness of typical homework, physical laboratories, the VCVD laboratory, and internship projects

4.3 | Data analysis

4.3.1 | Model maps

In a prior study, the laboratory notebooks kept by each team were analyzed in order to create Model Maps, an information-rich, chronological representation of the solution path that was followed by the student team. The development and construction of the Model Maps is briefly summarized below; more information can be found in Sherrett et al. (2013).

The Model Maps were constructed by transforming the information found in the laboratory notebooks and triangulating it with the meeting transcripts mentioned previously and other assignment deliverables. In this way, a team's solution to the laboratory project, which can take up to 60 hours, is reduced to a one-page graphical representation that provides information regarding the model components they used. Model Maps also connect the model components to the ways that they inform experimental runs by associating characteristics with specific symbols. Finally, additional descriptors further elaborate the modeling process such as identification of model components that are clearly incorrect or sources used in information gathering. All of these features are organized along a line representing the chronological progression of the student team's solution process. Two researchers coded the laboratory notebooks independently and then iterated the code book until sufficient inter-rater reliability was achieved (Cohen's kappa: Model Components = 0.8; Experimental Runs = 0.83).

4.3.2 | Creative thinking framework

In this work, the unit of analysis is the *group*. Model Maps created for prior work (Nefcy, Champagne, & Koretsky, 2013) served as the data source to determine elements of divergent thinking while reactor performance and team assessment score were used as indicators of quality of solution (Table 1). Convergent thinking was not directly measured here, but is an important contributor to solution quality. Table 1 outlines how the elements of divergent thinking and quality of solution were quantified.

Elements of the team's divergent thinking were characterized as follows. *Fluency*, which is defined as the number of ideas, was quantified as the number of components in the Model Map. *Flexibility*, relating to the different types of ideas, was quantified in two ways. One, the proportion of qualitative ideas, as opposed to quantitative ideas. Teams more commonly utilized quantitative components (equations, proportions) rather than qualitative components (on average, teams had 71% quantitative components and 29% qualitative components), so teams that utilize a higher proportion of qualitative components are denoted as being more flexible. Two, the total number of subcategories of model map components covered. Thus, being flexible also means that a team considering a variety of equations, theories, or relationships that relate to different elements of the CVD process. *Originality* was quantified by the proportion of unique components and total number of unique components present on their Model Map. A component was categorized as unique if none of the other 17 teams had it included on their Model Map. Finally, the quality of the solution, was quantified in terms of the reactor performance, an output generated within the VCVD software that considers multiple design objectives (e.g., film uniformity, gas utilization, process time, experimental cost), and the team's final grade, which included the instructor's assessment of the all of the team's deliverables as well as the reactor performance.

4.3.3 | Interview analysis

Student and expert interviews were analyzed separately. Student responses to the prompt shown in Figure 2 were translated into an electronic schematic, and aggregated onto a single scale. Comments were not included on the aggregated scale. Two students did not indicate a position for physical laboratories. Placement of position indicators, displayed as an "x," was maintained. Transcript excerpts were then coded in an emergent process to reflect common justifications of placement. Experts' interviews were coded to determine their perspectives on how the open-endedness of the VCVD compared to real engineering work. We present the aggregated student electronic schematic and representative excerpts from students and experts.

5 | RESULTS

The findings are organized to address our research questions. We first use examples of two teams (Teams A and B), to illustrate the analysis process and demonstrate how we characterize the divergent thinking in the VCVD project using Model Maps. Next, we examine the relationship between divergent thinking and solution quality, followed by a within subjects comparison of divergent thinking of student teams

TABLE 1 Creativity analysis framework

	Aspect	Definition	Model map quantity/Performance metric
Indicators of divergent thinking	Fluency	Number of ideas	Number of components in the Model Map
	Flexibility	Different types of ideas	Proportion of qualitative ideas (Qual/Total)
			Number of sub-categories covered
	Originality	Novelty of ideas	Number of unique components
			Proportion of unique components
Indicators of quality of solution			Reactor performance
			Assessment score (grade)

TABLE 2 Elements of divergent thinking in the VCVD project

		Average	SD	Range
Fluency		14.3	4.8	8-25
Flexibility	Qual/T	29%	11%	9-44%
	Number of Categories	5.8	1.7	2-8
Originality	Number	2.8	2.7	0-10
	Proportion	17%	10%	0-40%

in virtual and physical laboratories, and of expert teams in the virtual laboratory. Finally, we present a summary of participants' perceptions of open-endedness from the interview analyses.

5.1 | Divergent thinking in the virtual laboratories

Table 2 summarizes the elements of divergent thinking of the student teams working on the VCVD project.

On average, teams had a fluency of 14, corresponding to 14 components on a Model Maps. In terms of flexibility, teams addressed an average of about 6 different categories and had a smaller proportion of qualitative components than quantitative components (29% compared to 71%). Teams had an average of about 3 original ideas, comprising 17% of their total components.

Teams A and B represent a wide range of divergent thinking demonstrated in the cohort''s Model Maps. Team A (Figure 3) represents a team with the lowest fluency (8 components), average flexibility (30% qualitative components, covering 6 categories) and lowest originality (0 components). Their components comprise primarily quantitative components that were based on fundamental chemical engineering principles that were also considered by many other teams: the ideal gas law, a material balance, and basic statistics such as utilizing a Design of Experiments or considering confidence intervals.

Team B (Figure 4) had the highest fluency (25 components) and highest originality of any team (10 unique components, which is 40% of their total). This team had several components that were not present in any other team's Model Map, such as a concentration equation from a journal paper and multiple qualitative relationships relating different process variables (such as “lower pressure increases radial diffusion” and “higher flow rate decreases depletion”). Team B also had above-average flexibility in terms of number of categories covered (8), but below-average flexibility in terms of proportion of qualitative components (28%).

5.2 | Relationship between divergent thinking and quality of solution

In considering the indicators of quality of solution, teams had an average normalized reactor performance of 88% and project grade of 85% (Table 3).

Many elements of divergent thinking were statistically significantly correlated to each other (Table 4). Fluency significantly positively correlated with flexibility (both proportion of qualitative components and number of categories) and originality (both the total number of unique components and the proportion of original components). The two measures of flexibility significantly positively correlated with each other, and both measures of originality correlated positively with each other. One measure of flexibility (number of categories) correlated to one measure of originality (number). However, none of the five measures of divergent thinking significantly correlated with either indicator of quality of solution. Moreover, the measures of quality also did not significantly correlate.

Further illustrating this finding, in comparing the quality of solution indicators of Team A and Team B (Table 5), Team A achieved a higher reactor performance despite having lower divergent thinking measures; additionally, their project grade was lower than Team B.

5.3 | Comparing divergent thinking between the virtual and physical laboratories

Table 6 shows how divergent thinking compares between the laboratory projects according to an ANOVA test. Several elements of divergent thinking were statistically significantly higher in the virtual laboratory project than the physical laboratory projects including: fluency, number of original components, and proportion of original components. Overall, there were also more original components in the virtual laboratory (81) compared to the physical laboratories (12 or 13). Because there were far fewer components, there was not a distinct categorization of the types of components in the physical

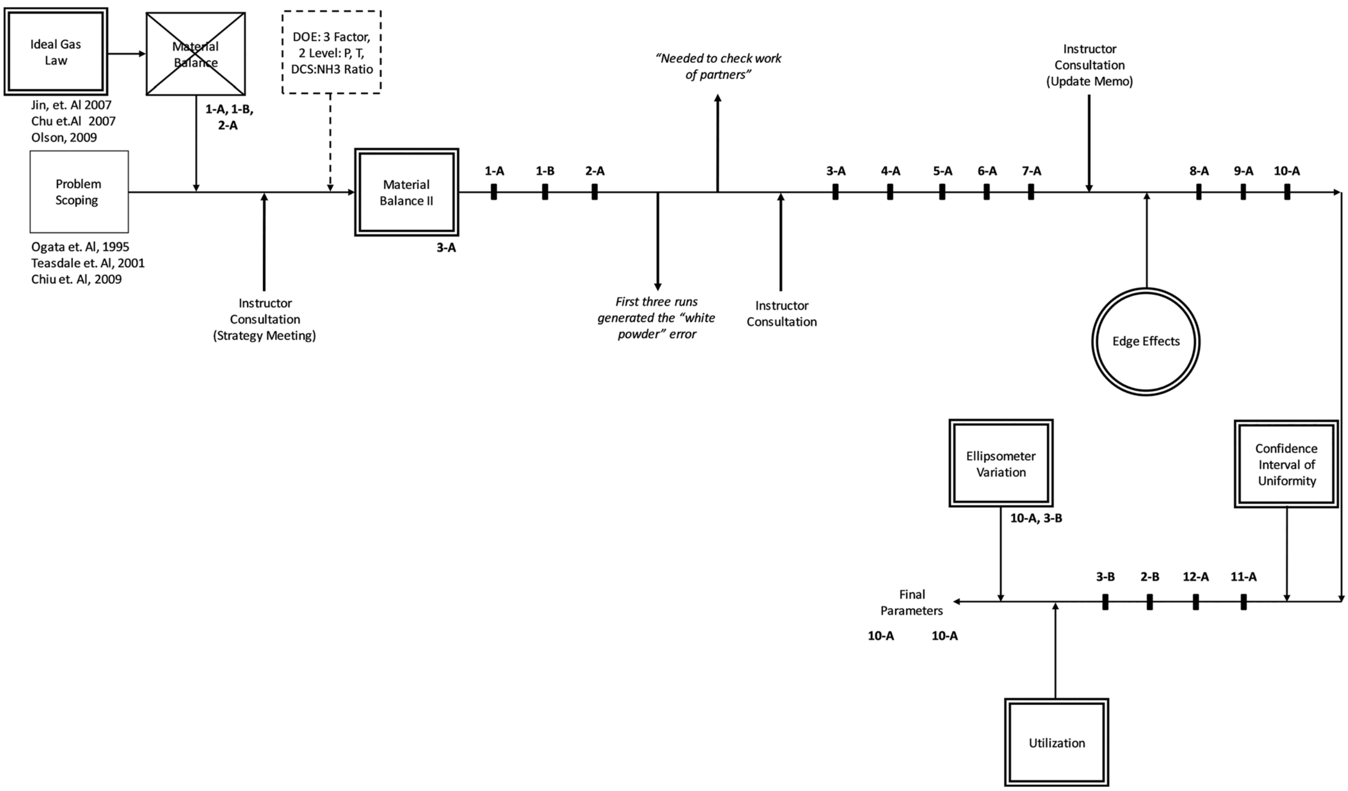

FIGURE 3 Model map of team A (lower divergent thinking)

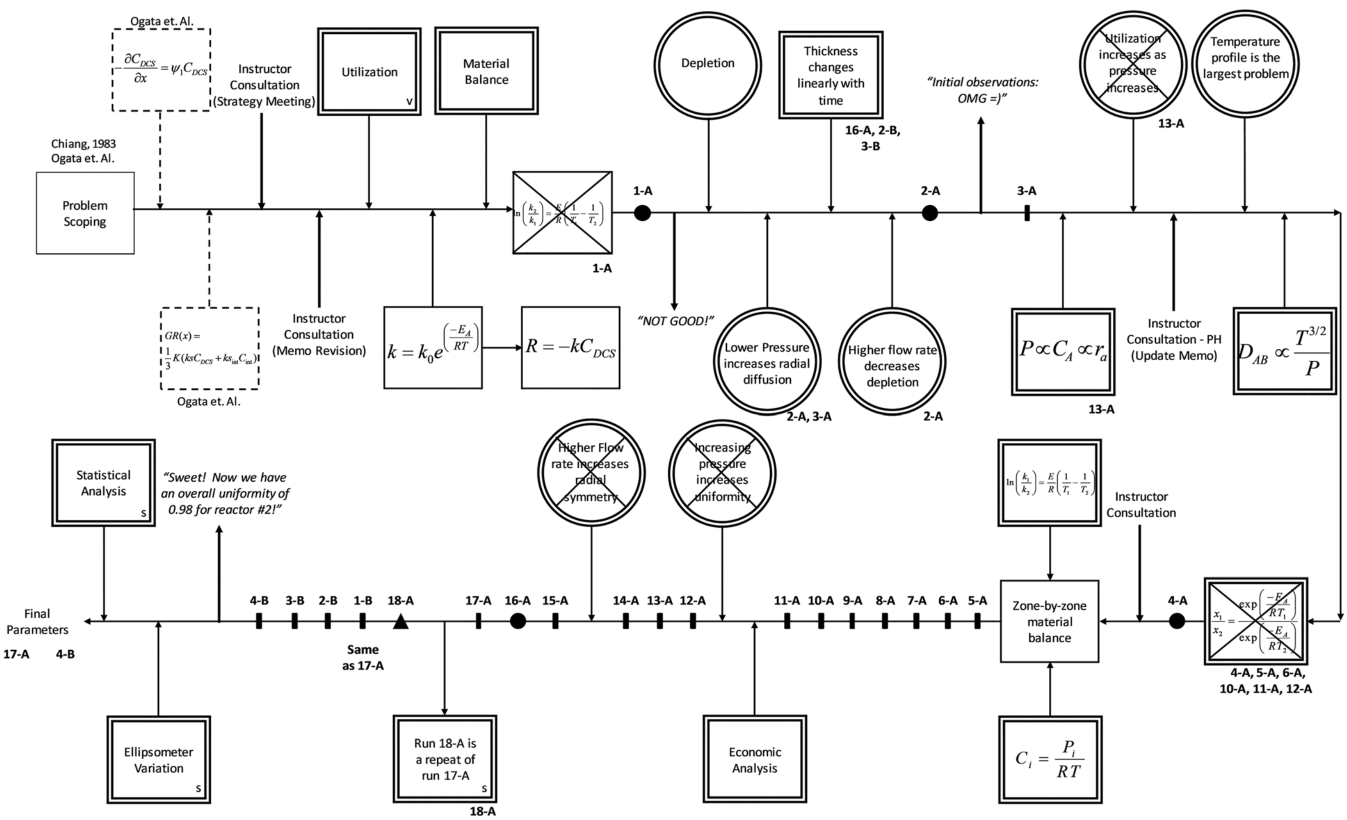

FIGURE 4 Model map of team B (higher divergent thinking)

laboratories; therefore, the flexibility in terms of number of categories was not considered for physical laboratories.

Table 7 shows the results of a Pearson's correlation analysis between divergent thinking and quality of solution in the virtual laboratory project and the physical laboratory projects. Many elements of divergent thinking in the virtual laboratory project correlate to divergent thinking in both of the physical laboratory projects. Fluency, flexibility, and originality in the virtual laboratory project also correlate to solution quality (grade) in both physical laboratory projects. Many elements of divergent thinking in one physical laboratory project correlate to divergent thinking in the other. Grades in each physical laboratory project correlate to each other, while grades in the virtual laboratory project do not correlate to grades in the physical laboratory project.

TABLE 3 Quality of solutions in the VCVD project

	Average	SD	Range
Reactor performance	88%	3.2%	80-93%
Grade	85%	6.1%	73-97%

5.4 | Comparing divergent thinking between students and experts in the virtual laboratory

Table 8 shows how elements of divergent thinking compare in the VCVD project between experts and students. The only statistically significant difference found was that experts had approximately twice as high a proportion of original ideas than students.

5.5 | Investigating how participants rank open-endedness of the virtual laboratory

Figure 5 shows how the nine interview participants rated each project on a scale from constrained to open-ended. In general, the activity of internships was indicated as being the most open-ended of the four activities, followed by the VCVD Laboratory. However, in two cases students placed the VCVD Laboratory as the most open-ended of the four. Typical Homework was indicated as the most constrained by all participants except for one, in which physical laboratories was indicated as most constrained, followed by homework.

TABLE 4 Pearson's correlation analysis of divergent and quality of solution

			Divergent thinking				Quality of solution	
			Flexibility (Qual/T)	Flexibility (Number of Categories)	Originality (Number)	Originality (Proportion)	Reactor performance	Grade
Divergent thinking	Fluency	Pearson correlation	0.518[a]	**0.801**[b]	**0.874**[b]	**0.669**[b]	0.101	0.379
		P-value	0.048	0.000	0.000	0.006	0.721	0.163
	Flexibility (Qual/T)	Pearson correlation		**0.584**[a]	0.353	0.277	0.184	0.108
		P-value		0.022	0.197	0.318	0.512	0.701
	Flexibility (Number of Categories)	Pearson correlation			**0.634**[a]	0.451	0.264	0.415
		P-value			0.011	0.092	0.341	0.124
	Originality (Number)	Pearson correlation				**0.911**[b]	0.099	0.099
		P-value				0.000	0.725	0.725
	Originality (Proportion)	Pearson correlation					0.163	-0.091
		P-value)					0.561	0.748
Quality of solution	Reactor performance	Pearson correlation						0.205
		P-value						0.464

[a]Denotes significant correlation at *P*-value < .05.
[b]Denotes significant correlation at *P*-value < .01.

TABLE 5 Comparing elements of divergent thinking and quality of solution for Teams A and B

			Team A	Team B
Divergent Thinking	Fluency		8	25
	Flexibility	Qual/T	30%	28%
		Number of categories	6	8
	Originality	Number	0	10
		proportion	0%	40%
Quality of Solution	Reactor performance		90%	86%
	Project grade		80%	86%

TABLE 6 Comparing elements of divergent thinking in the virtual and physical laboratories

		Average fluency	Average flexibility Qual/T	Average originality		Overall unique components†
				Number	Proportion	
Virtual laboratory (VCVD)		14.3*	70%	2.8*	20%*	81
Physical laboratories	PL1	4.0*	80%	0.1*	2%*	12
	PL2	4.9*	70%	0.3*	5%*	13

*Denotes a significant difference found with P-value < .05.†Unique components were summed across all 15 teams and no statistical analysis was performed.

Participants elaborated on their rankings during the interviews. For example, student Chris called the VCVD Laboratory project "by far the most open-ended thing I've done," and student Kelly said, it "was definitely more open-ended, because especially at the final meeting when we had, all the groups presented, we could see that no two groups approached it in the same way." Student Jamie connects the virtual laboratory to creativity saying, "you're trying to write your own procedure, and write your own where to start, and so that was a whole new component that I don't think we've really been asked to do before."

The experts found the project to be consistent with the authentic work they had done in industrial practice. Expert Charlie mentioned, "there have been a number of cases where I have had to design a process, develop a process, and the approach we took with this one, it was very, very similar." Expert David elaborated, "So I think it's [the VCVD project] important because if that's what we expect [engineers] to be able to do, we need to get students an opportunity to get those skills in that environment, right."

6 | DISCUSSION

In this study, we examined how elements of creative thinking manifest in teams' work products as they completed engineering laboratory projects in a university environment. We operationalize creative thinking in this context as toggling between divergent and convergent thinking to create a high-quality solution. The findings demonstrate that the virtual laboratory project affords greater opportunities for divergent thinking than the traditional physical laboratory projects, as has been suggested by other researchers who speculate that virtual environments encourage creativity (Abulrub et al., 2011; Balamuralithara & Woods, 2007). However, consistent with reports in the literature (Starkey et al., 2016), we found the relationship between divergent thinking and solution quality is complex, and more divergent thinking alone did not lead to higher quality solutions.

This study has several limitations. First, rather than a microgenetic approach where we analyze actual interaction data between team members, we infer information about teams' divergent thinking from an artifact of their work: their laboratory notebooks. Although elements of the resulting Model Maps allow characterization of elements of divergent thinking, they are indirect measures of actual student thinking. However, using Model Maps allows for a broader sample that would be untenable with a microgenetic approach (18 teams over three projects). Second, our study is limited to one laboratory class at one university with one population of students, and the results should be considered with this context in mind.

The elements of divergent thinking that we measured seem to be related within and across projects. All elements of divergent thinking in the virtual laboratory project correlated to each other (Table 4), and several elements of divergent thinking in the virtual laboratory project correlated significantly and positively to elements of divergent thinking in the physical laboratories (Table 7). Similarly, elements of divergent thinking in the PL1 project correlated to elements of divergent thinking in the PL2 project. These findings imply that teams that tended to exhibit more divergent thinking did so in all three contexts. Teams working on the virtual laboratory project exhibited significantly more elements of divergent thinking than in any other project. Although the sequence of the laboratories may be a contributing factor (students completed the two physical laboratory projects before doing the virtual laboratory project), student interviews show their experiences in the projects were very different. Interview responses (e.g., "no two groups approached it [the virtual laboratory] in the same way") indicate that the open-ended environment of the virtual environment provides students greater opportunity to practice the divergent thinking that may help them develop into creative engineers. Students also ranked the virtual laboratory high on a scale of open-endedness, approaching that of their internship experiences, while they considered the physical laboratory projects more constrained (Figure 5).

Experts had a higher proportion of unique ideas compared to students, but otherwise, experts and students were not significantly different in elements of divergent thinking in the virtual laboratory project, and the measured values were very close in magnitude. This finding suggests that in the virtual laboratory project, student teams were able to engage in divergent thinking to a similar degree as the practicing engineers, at least by the measures used in this study. This finding was supported by the interviews with experts who articulated similarities between the open-ended, ill-structured virtual laboratory environment and their own work in practice, and is further supported by prior work finding that divergent thinking leads students to develop their expertise (Christiaans & Venselaar, 2005). Their statements support the premise of the instructional design of the virtual laboratory; placing students in a context to do real engineering work will allow them to engage in practices (e.g., divergent thinking) needed

TABLE 7 Pearson's correlation analysis of divergent and convergent thinking in the virtual and physical laboratories

			PL1					PL2				
			Fluency	Flexibility (Qual/T)	Originality (Number)	Originality (Proportion)	Grade	Fluency	Flexibility (Qual/T)	Originality (Number)	Originality (Proportion)	Grade
VCVD	*Fluency*	Pearson correlation	**0.758**[b]	**0.670**[b]	**0.778**[b]	**0.785**[b]	**0.830**[b]	0.503	0.444	**0.673**[b]	**0.626**[*]	**0.743**[b]
		P-Value	0.001	0.006	0.001	0.001	0.000	0.056	0.098	0.006	0.013	0.002
	Flexibility (Qual/T)	Pearson Correlation	**0.636**[a]	**0.581**[a]	0.052	0.045	**0.599**[a]	0.477	**0.652**[b]	0.118	0.128	**0.566**[a]
		P-Value	0.011	0.023	0.855	0.873	0.018	0.072	0.008	0.674	0.649	0.028
	Originality (Number)	Pearson Correlation	**0.635**[a]	0.446	**0.713**[b]	**.740**[b]	**0.583**[a]	**0.656**[b]	0.489	**0.575**[a]	**0.529**[a]	**0.515**[a]
		P-Value	0.011	0.096	0.003	0.002	0.022	0.008	0.065	0.025	0.042	0.049
	Originality (Proportion)	Pearson Correlation	**0.570**[a]	0.296	0.487	0.508	0.427	**0.676**[b]	0.513	0.447	0.427	0.436
		P-Value	0.026	0.285	0.066	0.053	0.113	0.006	0.051	0.095	0.113	0.105
	Reactor Performance	Pearson Correlation	0.006	-0.136	-0.078	-0.098	0.181	-0.157	-0.118	-0.014	-0.003	0.106
		P-Value	0.984	0.630	0.783	0.729	0.517	0.577	0.675	0.960	0.990	0.708
	Grade	Pearson Correlation	0.175	0.314	0.406	0.375	0.472	-0.304	-0.224	0.456	0.444	0.474
		P-Value	0.532	0.255	0.133	0.168	0.076	0.271	0.422	0.088	0.097	0.074
PL1	*Fluency*	Pearson Correlation		**0.712**[b]	**0.537**[a]	**.521**[a]	**.853**[b]	**0.614**[a]	**0.642**[b]	**0.637**[a]	**0.633**[a]	**0.652**[b]
		P-Value		0.003	0.039	0.047	0.000	0.015	0.010	0.011	0.011	0.008
	Flexibility (Qual/T)	Pearson Correlation			0.412	0.416	**0.721**[b]	0.426	0.499	0.248	0.202	**0.678**[b]
		P-Value			0.127	0.123	0.002	0.113	0.058	0.373	0.470	0.005
	Originality (Number)	Pearson Correlation				**0.996**[b]	**0.552**[a]	0.477	0.264	**0.844**[b]	**0.777**[b]	0.420
		P-Value				0.000	0.033	0.072	0.342	0.000	0.001	0.119
	Originality (Proportion)	Pearson Correlation					**0.534**[a]	0.487	0.273	**0.813**[b]	**0.742**[b]	0.400
		P-Value					0.040	0.066	0.324	0.000	0.002	0.140
	Grade	Pearson Correlation						0.324	0.309	**0.619**[a]	**0.609**[a]	**0.816**[b]
		P-Value						0.239	0.263	0.014	0.016	0.000

(Continues)

TABLE 7 (Continued)

			PL1					PL2				
			Fluency	Flexibility (Qual/T)	Originality (Number)	Originality (Proportion)	Grade	Fluency	Flexibility (Qual/T)	Originality (Number)	Originality (Proportion)	Grade
PL2	*Fluency*	Pearson Correlation							**0.838**[b]	0.385	0.352	0.314
		P-Value							0.000	0.157	0.198	0.255
	Flexibility (Qual/T)	Pearson Correlation								0.290	0.288	0.302
		P-Value								0.294	0.298	0.274
	Originality (Number)	Pearson Correlation									**0.993**[b]	0.429
		P-Value									0.000	0.111
	Originality (Proportion)	Pearson Correlation										0.411
		P-Value										0.128

[a]Denotes significant correlation at *P*-value < .05.
[b]Denotes significant correlation at *P*-value < .01.

in the profession. However, more research is needed to identify the similarities and differences in the experts' approaches. Although there is not *one* right path to a solution, it can be argued that there are common ways professionals go about to optimize a chemical vapor deposition process. Case-based knowledge could allow experts to find a more direct path limiting their need to explore a higher number options (fluency) or a wider variety of options (flexibility) in order to find a solution path that made sense. However, only one of the three expert teams had specific experience in CVD. Thus, in two cases, the experts only had more general engineering experience upon which to draw.

There was not a significant correlation between divergent thinking measures and quality of solution measures in the virtual laboratory project (Table 4). This result implies that divergent thinking alone, at least by how it is characterized in this study, does not lead to high quality solutions, as supported by other researchers (Starkey et al., 2016). Rather, the relation between divergent thinking and quality of creative solutions is more complex. This study did not independently compare the quality of the teams' convergent thinking. Research is needed to examine the ways that convergent thinking processes interact with the ideas generated to influence solution quality. Such research design is challenging since each team's calculations and procedures develop from different starting points towards their creative solution. Consequently, rather than applying a standard instrument to gauge convergent thinking quality, each team's solution path must be uniquely analyzed in the context of their evolving solution path.

The quality of the teams'' social interactions is also an important factor in producing high quality solutions (Jordan & Babrow, 2013). Our unit of analysis was the team, and the teams that showed greater elements of divergent thinking would at least need to be functioning well enough to inscribe those ideas in their notebooks. However, Starkey et al. (2016) found that student teams often abandon divergent ideas in favor of more conventional solution paths. In addition, creative thinking involves toggling between divergent and convergent thinking in ways that effectively ulitlize the team's collective domain and general process knowledge (Christiaans & Venselaar, 2005). More research is needed to explore the role of team interactions in effectively toggling between generating ideas and critically evaluating them as they pursue an engineering solution. That is, in addition to doing the technical work soundly, we must consider social interaction skills as well.

Although there were not significant correlations between divergent thinking and performance in the virtual laboratory project, there were significant correlations between elements of divergent thinking in the virtual laboratory project (fluency, flexibility, and number of original components) and performance in the physical laboratory projects. We conjecture that the traditionally higher performing students might both receive higher grades in typical chemical engineering laboratory assignments and exhibit more divergent thinking when given the opportunity in an open-ended project. From this perspective, the virtual laboratory project studied here has the potential to cultivate divergent thinking capabilities that will benefit students when they

TABLE 8 Comparing divergent thinking in the virtual laboratory between experts and students

	N	Fluency	Flexibility		Originality	
			Qual/T	Categories	Number	Proportion
Experts	3	15.7	27%	5.7	5.3	34%[a]
Students	15	14.3	30%	5.8	2.8	17%[a]

[a]Denotes significant correlation at *P*-value < .05.

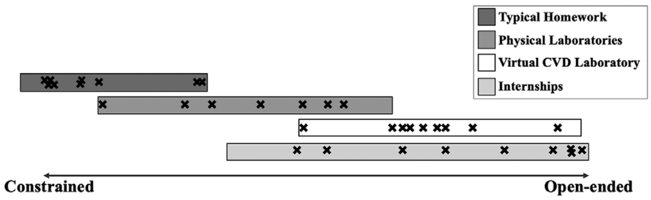

FIGURE 5 Student rankings of open-endedness of homework, physical laboratories, virtual laboratories and internships. The boxes can extend beyond the marked "x" when the student drew a range instead of a single point

work on "real world" problems as practicing engineers. However, grades in the virtual laboratory project also did not correlate to grades in either physical laboratory project or to measures of divergent thinking. Following our conjecture, students who may be typically rewarded in traditional laboratory environments may not be in the different context of the computer-based virtual laboratory. In other words, while divergent thinking is necessary for creative engineering problem solving, it is not sufficient to reach a high-quality solution. More research is needed characterizing how engineers toggle between divergent thinking and convergent thinking to create high-quality solutions and how that design skill can be rendered in the university context.

7 | CONCLUSIONS

This study contributes to the education community's understanding of engineering creativity by providing evidence of how student groups employ creative thinking in an undergraduate engineering laboratory context. We found that teams are encouraged to think more divergently in a computer-based virtual laboratory project than in two traditional physical laboratory projects. The open-endedness of the virtual laboratory project, coupled with the affordances of virtual data collection, allows student teams working together in-person to explore multiple different process possibilities without immediately committing to one "right" solution path, and without utilizing real materials, accruing operating costs or having safety consequences. Thus, they are encouraged to and supported in thinking creatively. Importantly, the creative thinking is situated within the work of a realistic engineering task.

These types of computer-assisted virtual environments appear to be a good resource for supporting divergent thinking in engineering students. However, teams who demonstrated more divergent thinking in the virtual laboratory project did not create higher quality solutions. We need a better understanding of the ways that divergent thinking leads to quality, and how engineers toggle between both divergent and convergent thinking to create quality solutions for complex problems. Just as it is clear that creativity is imperative in engineering, it is also clear that there is a need for continued study on the role and development of creativity in engineering work.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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APPENDIX A.: SAMPLE NOTEBOOK PAGE (DESCRIBING THE FIRST EXPERIMENTAL RUN)

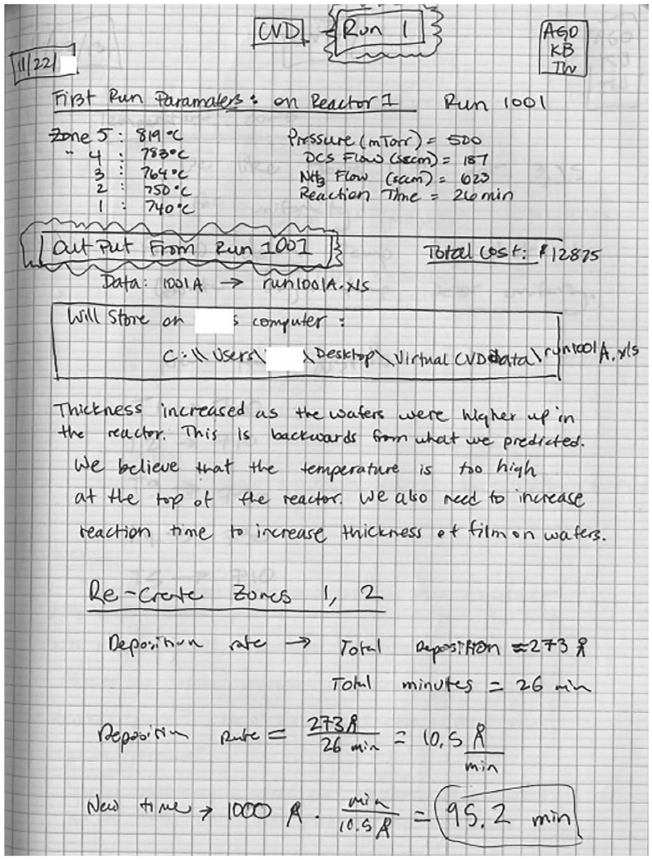

FIGURE A1 Sample page of a student laboratory notebook showing their first reactor run