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The Rise of Simulations in a Junior-level Fluid Mechanics Course

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Abstract

Simulation assignments were given to mechanical engineering students enrolled in two sections of an introductory fluid mechanics course. While some students were exposed to 3-4 simulations in a pre-requisite thermodynamics course, the majority had no prior simulation experience. The main goal of this study was to expand on implementation of simulations in undergraduate courses, and better understand the appropriate balance in student load. Considerations for student load brought on by the simulations include various attributes of the assignments such as, the selection, quantity, tasks associated with each simulation, grading criteria, credit assigned, and structure. All of these might influence student skill building, understanding of material, and problem-solving performance. This paper aims to address: (1) comparison of student load related to assignments, and (2) assessment of student understanding of select theoretical concepts. For the comparison of student load, highlighted differences in the course sections include: (a) number of simulation assignments (3 - 10), (b) number of application assignments (none or 3), and (c) the credit given to these assignments (2.5% or 15%). Surveys were administered to assess students' confidence in the usefulness of each simulation assignment, and also to have students identify each course topic, that simulations helped them to learn. Also highlighted here is one topic common to fluid mechanics, heat transfer, and an associated laboratory course: external flow over bluff and streamlined bodies. Students simulate the flow past a cylinder and/or airfoil, and design an app to investigate how various parameters impact lift and/or drag experienced by an object. Finally, laboratory experiments allow comparison of simulation results with experimental data.

Keywords — simulations; assessment; junior courses; thermo-fluids

Introduction

The implementation of computer-based simulations using multi-physics software in engineering education is of growing interest at the undergraduate [1-9]. Integration of simulations and inquiry-based learning (IBL) in undergraduate courses has been the focus of our practice and research for the last five years [5-9]. Our approach to digitized courses has been continuously improved to help us better understand what constitutes a well-designed course that simultaneously facilitates deep learning and mastering modern computational skills. This undertaking is not without challenges since, among other issues [7], instructors have distinctly subjective preferences regarding the delivery of material, assignment structure, and an associated assessment. The current study hones in on an assessment of simulation assignments in lecture-based courses and builds on the previous body of work. To provide the research context, we put forward an overview of our effort to introduce and grow the digital transformation and IBL in the mechanical engineering (ME) curriculum.

At the University of Hartford, the first computational skills are obtained in a graphic communication course and an engineering computer application course taken by all engineering majors in the freshmen year. The former incorporates AutoCAD, and the latter consists of computer programming, data science, and tools for solving problems (MATLAB, MS Excel). For mechanical engineering majors, another computer-aided design (CAD) course with SOLIDWORKS and ANSYS is encountered in the junior year. Most ME capstone projects are sourced from and sponsored by local industry and have at least one component that requires simulations. It was apparent to us that modern computational tools had been confined in their own courses while lecture-based courses had been taught using unchanged methods [7]. Moreover, we had been hearing from students that basic computational skills courses were placed far apart from the professional electives.

In response to the perceived issues, we have embedded simulation assignments and IBL in the thermo-fluids sequence. The choice of software is the result of the authors' prior success with a graduate multiphysics modeling course [9]. Our initial objective was to have a software tool that provided sufficient disciplinary breadth to address a range of engineering problems. The sequence starts with an introductory thermodynamics course in the sophomore year, and continues with fluid mechanics and heat transfer courses in the junior year. The thermodynamics course has four simulation assignments [6, 10]. The use of the software in the final project is limited due to the students' inexperience in simulations. The fluid mechanics and heat transfer courses contain up to ten simulations each and may incorporate application building [5].

The successful design of lecture-based courses with a simulation component requires four elements: the learning method, supporting materials, the evaluation method, and learning technology [8]. They are briefly described herein:

1. In-person instruction, richly illustrated and explored with simulations, is complemented with learning methods used outside classroom. These include reading on-line materials, watching instructional videos, and performing simulations. Exciting and relevant visuals help students understand complex concepts, systems, and interactions otherwise hard to see or imagine. This in turn facilitates student engagement and, ultimately, retention.
2. While we use simulations in the classroom to elucidate theoretical concepts and real-life applications, finite element analysis (FEA) and computational fluid dynamics (CFD) skills are obtained outside of classroom. Effective supporting materials are the cornerstone of our approach to simulation assignments. Simulation blogs, YouTube videos, and industry articles underpin skill learning. In addition, each assignment has Grading Criteria with valuable clues on various simulation aspects such as footnotes, hyperlinks, and an Appendix featuring multiple examples that are relevant to the given simulation.
3. Students' final grade is determined by performance on simulation assignments and three exams. Assignments have two components: structured (with step-by-step instructions) and unstructured (IBL). We use interviews with students throughout the semester and after the course(s), as well as instructors' observations to tweak individual assignments and the overall simulation assignment line-up for the upcoming semester.
4. Our online environment is the Blackboard® learning management system (LMS). Online delivery and activities support autonomous learning of modern computational skills, preserve classroom time devoted for theoretical concepts, and lighten the load on the instructor during office hours. It is our experience that office hours are then used efficiently for assistance and mentoring. This provides students with multiple chances to improve performance based on the instructor's input given before the assignment deadline.

This multi-faceted approach in and outside the classroom encourages students to continuously reflect on the connections between theory, practice, and simulations. On a course level, we facilitate a deeper understanding of complex theoretical concepts, use of modern computational tools, and development of students' research capacity. On a curricular level, we transition students from basic computer skills courses to discipline-specific courses with multiple simulation assignments and IBL, and, finally, to capstone projects and specialized professional electives that focus on advanced modeling and simulation.

As indicated before, instructors have preferences regarding the delivery of material, number and type (simulations and applications) of assignments, their configuration and depth (structured and unstructured), assessment of individual assignments as well as assignment weight within the specific course. For example, while one instructor may mandate 10 assignments distributed throughout the semester, the other may have three placed towards the end of the semester. We decided to study these differences using two sections of a fluid mechanics course that ran in parallel last fall in order to closely examine their benefits and drawbacks.

Methodology

A taxonomy is first developed here, and presented in Table 1, to highlight a range of potential levels of contribution to each element of lecture-based courses which includes simulations. The four elements, as previously stated in the introduction, include the learning method, supporting materials, the evaluation method, and learning technology. These elements have been examined and modified throughout the past five years and help categorize the efforts described in the present study, in which simulation assignments were part of two different sections of a lecture-based fluid mechanics course that ran in fall 2019. The instructors of these sections (Section A and B) have already been part of a team collaborating on the implementation of simulations and IBL in undergraduate curriculum. Sections A and B started with n = 12 and n = 20 students, respectively. These sections had different: (1) instructors; (2) number of assignments; (3) distribution of assignments; (4) assignment configurations; and (5) grading criteria. Grading of simulation assignments in Section B was also done by an instructor and a teaching assistant, with a separate tutoring/support system also offered. In Section A, grading was done solely by the instructor, and no additional tutoring/support system was offered outside of typical office hours. Sections A and B completed three and ten assignments, respectively. In section A, the assignments were: Water Purification Reactor, Discharging Tank, and Flow Past a Cylinder. In section B, the assignments were: Stationary Incompressible Flow over a Backstep, Non-Newtonian Flow, Swirl Flow around a Rotating Disk, Flow Past a Cylinder, Application: Flow Past a Cylinder, Inertial Focusing, Vibrations of a Disk Backed by an Air-Filled Cylinder, Eigenmodes of a Room, Automotive Muffler, and Helmolhtz Rezonator or Flow Around an Inclined NACA 0012 Airfoil.
For section B, "Application: Flow Past a Cylinder," was the only stand-alone app, and the other two apps were in the IBL portion of the assignment.

The only assignment that the two sections, A and B, had in common was Flow Past a Cylinder. It was deemed particularly useful since students encounter external flow over bluff and streamlined bodies in three junior-year courses: fluid mechanics, heat transfer, and an associated laboratory.

Table 1: Taxonomy for the design of lecture-based courses with a simulation component

	HIGH	**HIGHER**	**HIGHEST**	**GENERAL GOALS**
1 **LEARNING METHOD** (IN & OUTSIDE OF CLASSROOM)	• Exciting and relevant visuals	• Exciting and relevant visuals • Simulations to elucidate theory and application • Incorporate a rich blend of content into the classroom setting	• Exciting and relevant visuals • Simulations to elucidate theory and application • Incorporate a rich blend of content into the classroom setting • Use simulations to help students better understand important cause and effect relationships	• Help students visualize and understand material • Engage students • Retain students • Prepare students to analyze & design using modern software tools • Combine problem-, project-, and inquiry-based learning methodologies • Promote self-learning by requiring investigation beyond what is provided
2 **SUPPORTING MATERIALS** (OUTSIDE OF CLASSROOM)	• Access to on-line materials • Simulation tutorials • Performing simulations	• Access to on-line materials • Simulation tutorials • Performing simulations • Watching instructional videos	• Access to on-line materials • Simulation tutorials • Performing simulations • Watching instructional videos • Reading simulation blogs and industry articles	• Support learning both in and outside of classroom • Support learning of modern computational skills (FEA and CFD) outside of classroom • Challenge students to explore and test 'outside the box' ideas
3 **EVALUATION METHOD**	• Simulation assignments are a part of course grade	• Simulation assignments are 10%+ of course grade • Assignments have one component: structured only	• Simulation assignments are 15%+ of course grade • Assignments have two components: structured **AND** unstructured	• Help students master material and skills • Improve individual simulation assignments and an overall line-up for upcoming semester
4 **LEARNING TECHNOLOGY**	• Use of online environment, such as Blackboard® LMS • Use of commercial software, such as COMSOL Multiphysics®	• Use of online environment, such as Blackboard® LMS • Use of commercial software, such as COMSOL Multiphysics® • Autonomous and cooperative learning of computational skills using line-by-line instructions	• Use of online environment, such as Blackboard® LMS • Use of commercial software, such as COMSOL Multiphysics® • Autonomous and cooperative learning of computational skills using line-by-line instructions and IBL	• Preserve classroom time for theoretical concepts and in-person discussions • Preserve office hours to focus more on assistance and mentoring

The distribution of assignments in section A consisted of three simulations close to the end of the semester. Instructor A hypothesized that this placement would be helpful after theoretical topics had already been introduced and thoroughly discussed. Moreover, simulations provided an overview of some important subject matter right before the final. Section B had 10 simulations throughout the semester, each due in seven days, with the first one assigned in the first week of the semester. Instructor B preferred an early start for the following reasons: (1) early familiarization with the software, (2) immediate illustration of no-slip condition and velocity profiles, and (3) keeping students' interest in the material while covering theoretical topics such as unit conversion and fluid properties.

With regard to assignment configuration, Section A had structured assignments with step-by-step instructions, while Section B had both structured and unstructured (IBL) components within each assignment. In Section A, students had to complete simulations, auto generate (using software feature) technical reports, and write an essay which describes what they learned from each simulation assignment (150+ words). Section B had to complete simulations, auto generate and customize technical reports, and research further software capabilities and/or the topic itself. IBL and associated requirements are described in detail in these references [5-9].

With regard to assignment grading criteria, Section A was graded based on the completeness of the submitted Technical Reports, and clarity and succinctness of an essay. Section B had 75% of each assignment grade allocated to the structured and 25% to an IBL components. Instructor B hypothesized that 75% is a sufficient incentive for students to go through step-by-step instructions and gain valuable simulation experience (and credit) without much anxiety. Since the majority of students have issues working on simulations without support [7], IBL was just 25% of an assignment grade. The simulation assignments in Sections A and B were 2.5% and 15% of students' final grade in the course, respectively.

As mentioned before, we use interviews with students throughout the semester and after the course(s), as well as instructors' observations to tweak individual assignments and the overall simulation assignment line-up for the upcoming semester. In addition, in fall 2019 we collected quantitative and qualitative data that could help better understand student experiences with each simulation, as well as which course elements may have helped students understand and absorb fluid mechanics topics. Our two-part Survey on Simulations (A) and How I learned each topic (B) shown in Figs. 1-2, respectively, was given to both sections. Survey for Section A was administered in the last week of the semester. Surveys for Section B were administered at two points in the semester: upon completion of five and nine simulation assignments. Instructors hypothesized that (1) students will remember better simulations that are recently performed, and (2) surveying students in the last week of the semester would compete with other surveys and course evaluations.

In summary, there were differences in how the simulations were utilized in the two sections. Section A simulations were assigned as students were learning the last sets of topics. Section B had them distributed across the 16-week semester in a way that could coincide with or compete with the lecture topics. Simulation assignments during the semester are a task that students must attend to in addition to typical work.

SURVEY I: SIMULATIONS								
For each statement below, circle the number to the right that best describes your level of agreement with each statement, based on the given rating scale.								
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**
	Level of agreement:	**Strongly Disagree**	**Disagree**	**Somewhat disagree**	**Neutral**	**Somewhat agree**	**Agree**	**Strongly Agree**
Simulation # __: ____								
1	Sim # __ was useful in developing my simulations skills	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
2	Sim # __ had clear & detailed grading criteria	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
3	Sim # __ had informative supporting materials [Blog, YouTube, Other]	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
4	Please indicate any qualitative & quantitative changes to Sim # __ that you would implement in the future [More or less challenging IBL, more or less IBL items, etc.]							

Figure 1: Survey on Simulations (Note: Each Simulation had one of these surveys)

SURVEY II: HOW I LEARNED EACH TOPIC? Select all boxes that apply							
Factors that helped me understand these topics:	**Lecture**	**Simulations**	**In-Class Discussions**	**In-Class Problems**	**Homework Problems**	**BlackBoard Materials [Videos]**	**Other**
Ch 1: Intro & Basic Concepts	☐	☐	☐	☐	☐	☐	☐
Ch 2: Properties of Fluids	☐	☐	☐	☐	☐	☐	☐
Ch 3: Pressure & Fluid Statics	☐	☐	☐	☐	☐	☐	☐
Ch 4: Fluid Kinematcs	☐	☐	☐	☐	☐	☐	☐
Ch 5: Bernoulli & Energy Eqs.	☐	☐	☐	☐	☐	☐	☐
Ch 6: Momentum Analysis of Flow Systems	☐	☐	☐	☐	☐	☐	☐
Ch 7: Dimensional Analysis	☐	☐	☐	☐	☐	☐	☐
Ch 8: Internal Flow	☐	☐	☐	☐	☐	☐	☐
Ch 11: External Flow: Drag & Lift	☐	☐	☐	☐	☐	☐	☐
Your comments & suggestions							

Figure 2: Survey on how I learned each topic?

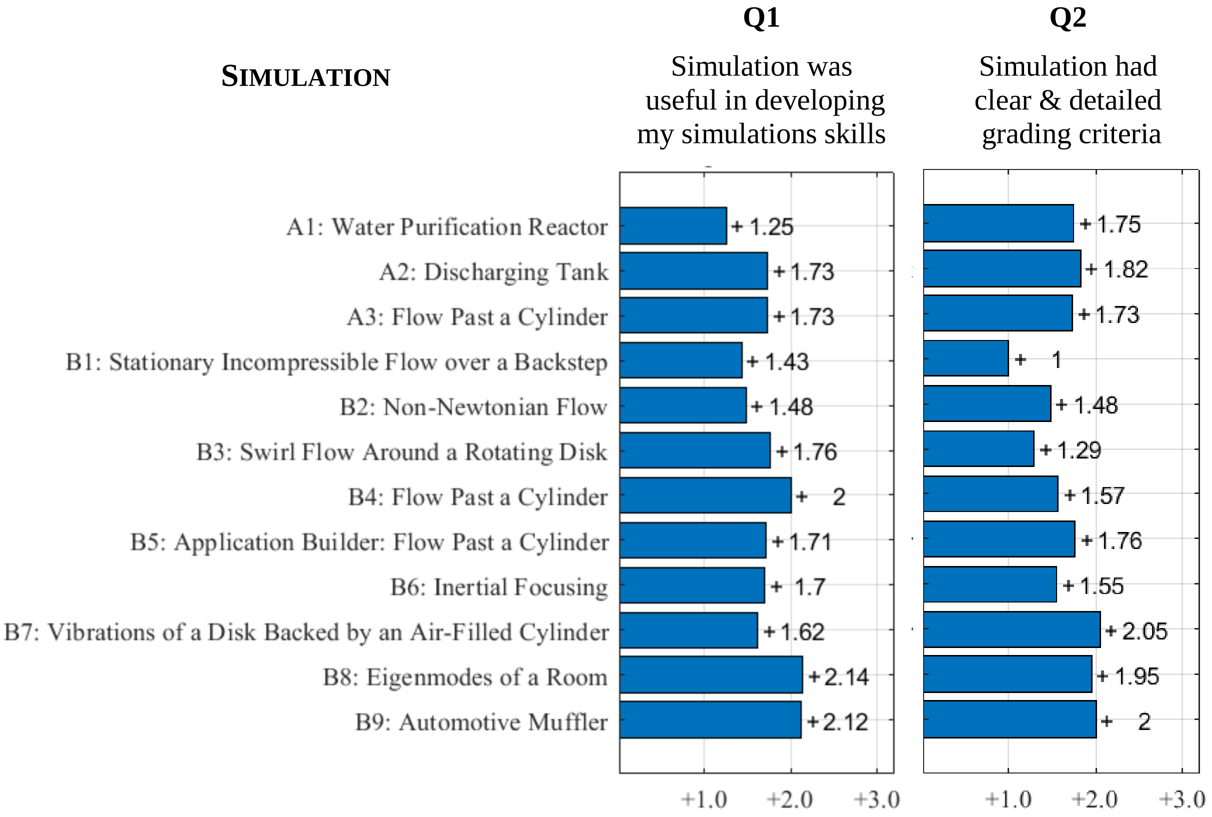
When in sync, i.e., distributed and completed across the semester in a way that coincides with delivery of each course topic, simulations may help students, but if students do not execute these simulations in sync, it could distract from other tasks. In both cases, students had a chance to deepen their understanding of the course material, learn modern computational skills, and improve their career-readiness.

Results

Results from the administered surveys are described here. Table 2 shows the results of students' aggregate level of agreement with the first teo survey questions (Q1 and Q2). Each of these questions were on a Likert scale extending from -3 to +3. Hence, a negative average would indicate students were mostly in disagreement with the statements in each survey question.

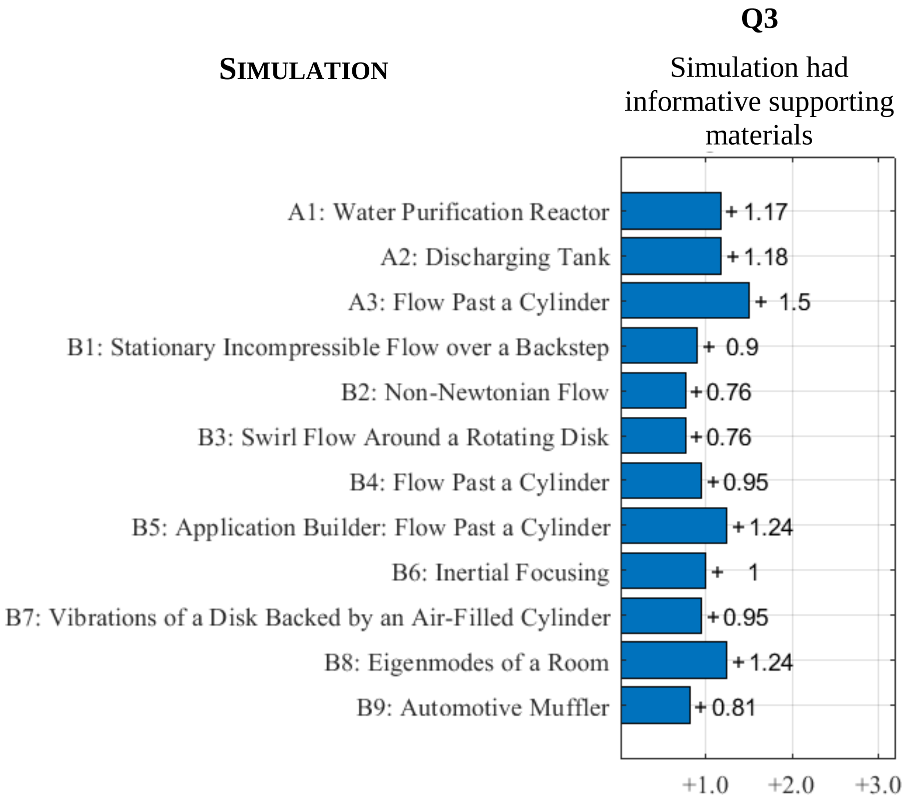
Simulation 10B is not included here because the survey was administered before students completed this simulation. Overall, students were in agreement that the simulation assignments were useful in developing their simulations skills (Q1), and that the simulations had clear & detailed grading criteria (Q2). They somewhat agreed that the simulations had informative supporting materials. It should be noted that for Section A, besides the simulation instructions, there were no other supporting materials which were shared which had the direct purpose of supporting the simulation work. Section B had a student tutor, and lots of supporting material that students may or may not have spent time reading.

Table 2: Results of Likert scale survey Q1 and Q2 with level of agreement ranging from -3 to +3



Results of level of agreement as indicated on a Likert scale extending from -3 to +3, showed a similar overall average for both sections of the fluid mechanics course. Looking at specific attributes of each course, in section A, Simulation 3A: Flow Over a Cylinder had the best average. In section B, Simulations 8B and 9B had some of the highest averages, and the highest average when removing answers to question 3. It appears that although section B had much more materials on the LMS, i.e. videos, students did not feel that the materials were supportive of simulations. Hence, it is suggested that the level of utility offered by supporting materials, be revisited, maximized, or not included, as it can take away from their intended effect.

Table 3: Results of Likert scale survey Q3 with level of agreement ranging from -3 to +3



With the overall averages of all quantitative responses to Q1, Q2, and Q3 averaging at about ~ +1.5 for both sections, the data suggests that the number of simulation assignments did not impact students feeling about the usefulness of the simulations. They simply tend to agree/somewhat agree that the assignments were useful, and had clear grading criteria, and somewhat supportive materials.

Table 4: Results for All Survey Questions

All simulations	Q1, Q2, and Q3
	(-3, -2, -1, 0, 1, 2, 3)
Section A	+ 1.5
Section B	+ 1.4

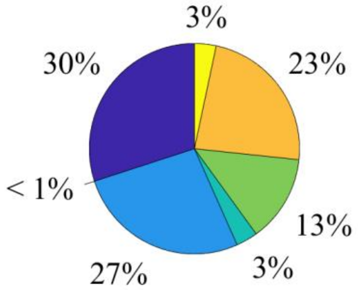
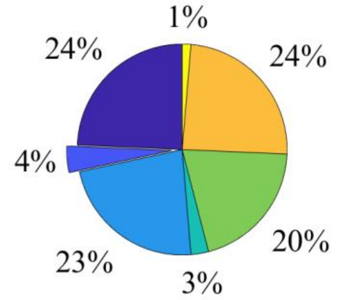
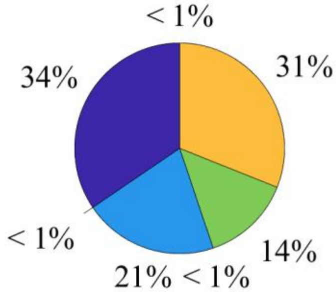
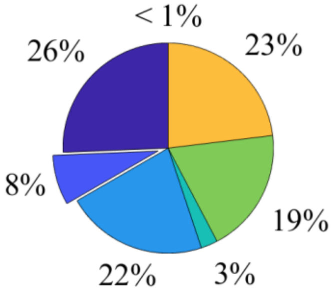
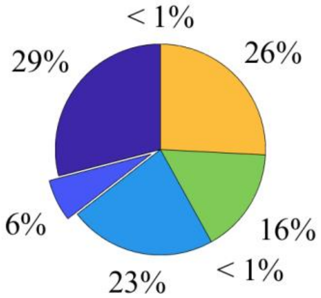
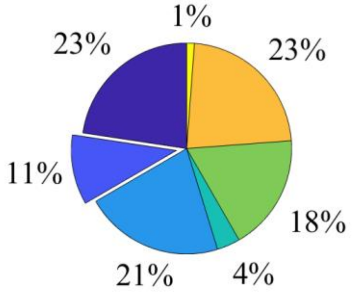
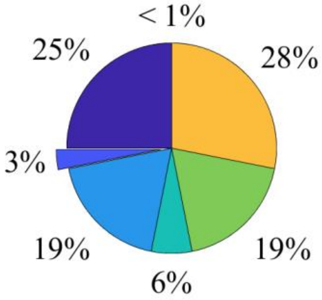
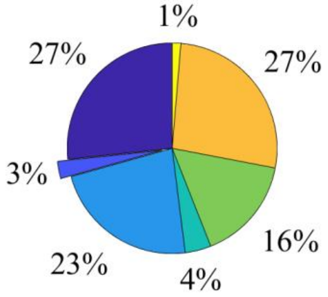
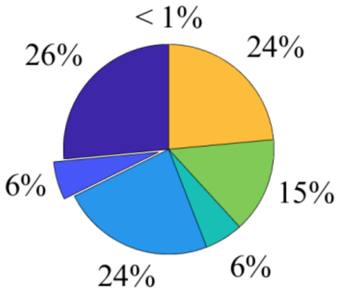
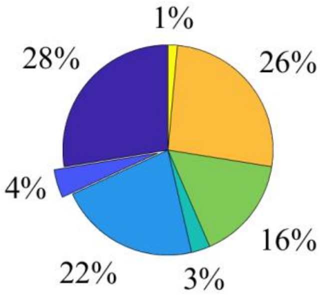
The second part of the survey was aimed at identifying specific factors or approaches that helped students understand topics covered in the course.

The extent to which each approach contributed to students' understanding of a chapter can be determined in the following way. By taking a tally of students who chose each approach, and dividing it by the total number of approaches which were identified for that chapter, a ratio can be established. This ratio, in percentage can represent the level of contribution that the identified approach had on students' learning of the topic. For example, in section A, the 12 students gave a total of 30 answers, selecting the approaches that they felt helped them learn the subject matter in chapter 1 (Intro & Basic Concepts). Out of these 30 selections, there were nine who selected "Lecture," so it could be stated that 9/30 or 30% of the topic was learned through lecture, while 70% was learned through other methods. Again, this is based on students' feelings about their experience, and it is not a direct comment on how their brains actually learned the material. Redoing a study like this coupled with some type of Concept Inventory Tests could help provide even more insight. Tables 5 and 6 list some of the main topics by textbook chapter and highlights the percentage of answers given by students in which they identified each approach that helped them to understand each topic. . Table 5 gives these results for data available for both Sections A and B, while Table 6 specifies results for data that was only readily available for section A. The approaches highlighted in both tables include: the lecture; simulations; in-class discussions; homework (HW), in-class problems; or some other factor. This includes student feedback on how they learned content from chapter 4: Fluid Kinematics, 8: Internal Flow; and 9: External Flow Drag & Lift. The methods which students most identified as contributing to helping them learn the content of each chapter were the lecture, in-class problems, in-class discussions, and homework. The contribution of simulations ranged from 0 to 11% depending on the chapter.

What is also interesting is that the level of contribution of simulations identified by students in comparison with the other methods such as lectures, discussions, HW, etc. was near ~6% for both sections. While 6% is a number that means that simulations are not going to replace a lecture or practice problems, what it also means is that if there were no simulations, students who learned from them would might miss out on 6% of how/what they would have learned. If the method of their learning was not there then what they actually learned might be missing, not because it was not taught but because it was not learned. These are the type of subtle differences in teacher-centered learning and student-centered learning. Whether it is the visualization or some other aspect of the inquiry based learning, this shows that simulations can augment the typical offering of a course, regardless of the instructor, or typical nature of the course delivery.

Toward the goal of continuous improvement, what is it that will contribute to the rise of simulations in thermo-fluids courses? Well, based on some of the data presented here, it can be seen that simulation assignments are not all equal (as can be expected) and there are some which students' found more valuable to their learning. Hence it is suggested that instead of focusing on the number of simulations, the value of each simulation be enhanced by careful development of the assignments, their complimentary nature with the lectures, discussions, and in-class, and HW problems, and other approaches utilized in a course. For example, a module that has multiple aspects that correspond with different topics in a course may prove to be more valuable to students than many simulations.

Table 5: What percentage of learning of content from each chapter do students attribute to simulations and other methods?

Chapter	Section A (n = 12)	Section B (n = 21)
1: Intro & Basic Concepts		
2: Properties of Fluids		
3: Pressure & Fluid Statics		
5: Bernoulli & Energy Eqs.		
6: Momentum Analysis of Flow Systems		

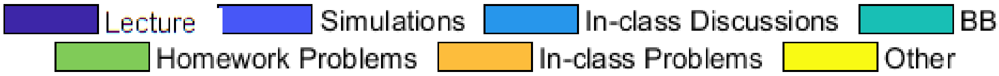
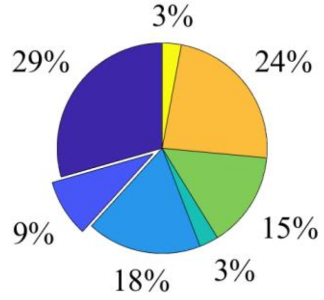
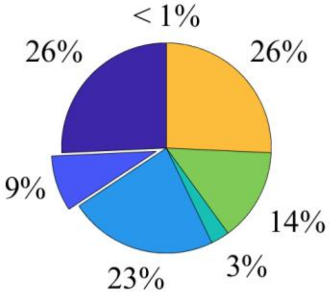
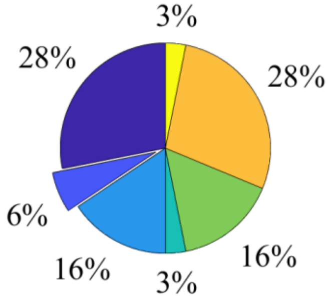
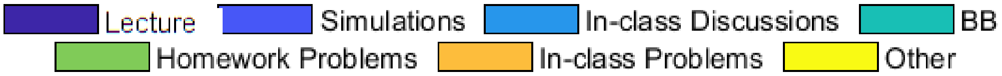


Table 6: What percentage of learning of content from each chapter do students attribute to simulations and other methods?

Chapter	Section A (n = 12)
4: Fluid Kinematics	
8: Internal Flow	
9: External Flow Drag & Lift	



In addition to the quantitative data presented, there was qualitative data that was obtained through the open ended questions on the surveys administered. Specifically, in students' responses to Survey II, in which they identified how they learned each topic, they had a chance to write comments and suggestions.

There were over 30 pieces of feedback received. These have been combined and summarized into the list in Table 5, to give a general gist of the course, and highlight areas for improvements that should be considered with regard to the course and simulations. An example of how comments were combined and summarized is given here. These two comments in Section B:

- "Maybe give some options for each sim such as for sim x give an option for ME and acoustics or other, this way students can focus on the concentration they care about/are most interested in"
- "While COMSOL simulations are interesting, perhaps more varied simulations would be helpful for those who aren't as interested in aerospace or air flow"

were combined into Table 7 as the following:

- About topics: need more variation for students with interests outside of aerospace

It should be noted, that these specific comments represent two of the many comments received, and not the majority of responses. While the feedback is noted constructively, instructor's retort here would be two-fold, in that there was a wide range of fluid mechanics simulation topics covered, and that it can be beneficial for students to become accustomed to engineering problems outside of their specific area of interest. With regard to the range of topics offered, they included: water (Sim 1), non-Newtonian flow (Sim 2), Swirl flow, mixing (Sim 3), flow past a cylinder (Sim 4), fluid in a pipe (Sim 6), vibration, air (Sim 7), acoustics, air (Sim 8), and muffler, air (Sim 9). It should be further noted that these last two garnered some of the highest ratings by students as previously indicated in Table 2.

Table 7: Student feedback as per surveys on the course and simulations

Section A	Section B
General comments related to the course: ○ In-class lectures and homework were great ○ Weekly quizzes were very helpful ○ Homework problems should be more collaborative/ more visualization/project	General comments related to the course: ○ Class was great ○ In-class problems helped ○ Solutions for the in-class problems should be included on-line
Comments on simulations: ○ N/a	Comments on simulations: ○ General: Simulations were fun and interesting ○ About topics: need more variation for students with interests outside of aerospace ○ About understanding: they need to better help students understand fluids problem-solving and topics ○ About grading: simulations were graded harshly, and too large a part of the grade ○ About learning the software: more class time (or a separate class) could be spent to help students learn software basics

The feedback about the classes and courses themselves were mostly positive. Feedback about each class, but not specifically related to simulations, included "I had a great time in class and really enjoyed the teaching style!!" or "Fantastic course!" for Section A, and "this has been a great class," and "The instructor is very detailed on lessons and when solving class problems," in Section B.

The positive statements about the simulations were mostly general, and included the following for section B: "The majority of the simulations were good supplemental material," "the simulations are a great tool to have," "COMSOL simulations are interesting," and simulations were fun and challenging." The critical feedback related to the simulation topics, student understanding, grading, and learning the software, can be used to further improve the offering of simulation assignments.

Conclusions

This effort builds on authors' previously reported work on collaborative and inquiry-based learning utilizing simulations and applications. The present study reports on the implementation and assessment of simulation assignments in different sections of a lecture-based fluid mechanics course. While simulations did not play the dominant role in students learning of fluid mechanics, it did play a role for some, as ~15% of the students in the course, identified simulations as contributing to their learning of the subject matter. Upon identifying all of the approaches that helped students learn the subject matter including, the largest contributors near or above 20% were lectures, discussions, in-class problems, and HW problems. Simulations accounted for 6% of student answers provided, suggesting that simulations were responsible for 6% of their understanding of the subject matter. While the simulation assignments simultaneously allowed students to gain software skills within an authentic engineering learning environment, the 6% contribution to learning fluid mechanics is also valuable. While simulations have not risen to the point of surpassing lectures, etc. (nor do the authors argue that they should), they do augment students' learning. Without the simulations, that 6% might be lost, not because it was not taught, but because it was not learned. Hence, given the presented student-centered teaching and learning approach of inquiry based learning using simulations, the rise of simulations can help enhance students' learning of the curriculum. To help student achievement of learning outcomes, for example in a fluid mechanics course, it is suggested that implementation of simulations into engineering courses, focus more on complementing the lecture/ problems/ discussions, than on increasing the number of simulation assignments.

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