Numerical Simulation Challenge: a College-Industry Cooperation to Engage Students and Enhance Learning in Computational Fluid Dynamics and Finite Element Analysis

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Abstract:

Undergraduate students in Mechanical Engineering are progressively introduced to numerical simulation tools throughout the curriculum. Starting in the sixth semester, students learn the fundamentals of the Finite Element Method (FEM) and Finite Volume Method (FVM) through analytical concepts and MATLAB-based implementations for simple structural and fluid dynamics problems. In subsequent courses, FEM and FVM are applied to basic and intermediate engineering case studies using commercial CAE software. Building on this background, a senior-level elective course entitled Computational Simulation in Mechanical Engineering was designed to provide an integrated industry-driven experience in Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA), enrolling approximately 20 students per year. The same student cohort participates across two consecutive semesters, addressing a real industrial problem from both fluid and structural perspectives. The challenge involves cooperation between academia and an industrial partner specializing in mixing and processing equipment and is structured in four stages: (i) an introductory lecture delivered by an industry engineer presenting the design challenge, (ii) individualized follow-up meetings with student teams, (iii) submission of a technical report containing simulation results and proposed design improvements, and (iv) final evaluation and presentation of selected projects. Students work individually or in pairs to develop complete numerical models under academic supervision and industry mentoring. Performance is evaluated using a structured rubric combining academic criteria (model formulation, assumptions, boundary conditions, mesh quality, and technical communication) with industrial criteria (agreement with a validated reference model and feasibility of proposed improvements). Final grades are assigned on a 0–10 scale (approximately aligned with the A–F grading system) based on the submitted reports, and the highest-ranked teams are invited to present their results to industry engineers. To assess student engagement, a post-activity questionnaire was administered at the end of the second semester of the challenge. Across four years of implementation, at least 88% of participants reported that the industry-integrated challenge enhanced their learning of CAE tools. This paper presents the structure of the challenge and discusses student and industry perceptions of this academic–industrial collaboration.

INTRODUCTION

Computer Aided Engineering (CAE) has become a central component of modern mechanical engineering practice, enabling engineers to evaluate complex designs, explore alternatives, and predict performance under realistic operating conditions before physical prototyping. In this context, Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) are widely adopted tools across multiple industrial sectors, supporting decisions in process development, design optimization, structural integrity, reliability, and failure prevention. In industrial workflows, CFD is frequently applied to investigate fluid flow behavior, mixing systems, and aerodynamic performance, while FEA provides the foundation to evaluate stresses, strains, deformation fields, and safety margins under mechanical and thermal loads [1], [2]. These methods are increasingly embedded in real engineering practice due to advances in computing power and the maturity of commercial solvers, which have expanded the use of simulation in mechanical, aerospace, automotive, and manufacturing contexts [3].

Across engineering sectors, simulation is now routinely used to reduce physical testing cycles, support design decisions earlier in development, and investigate failure scenarios under controlled numerical experiments. CFD is firmly established as a central approach in aerodynamic analysis and flow prediction, with classical references highlighting its relevance to engineering decision-making and performance assessment [4]. In parallel, FEA has evolved into a mature computational discipline supported by rigorous formulations and extensive industrial practice; foundational works consolidate its role in modern structural and continuum mechanics analysis [2]. Together, these perspectives reinforce that simulation is not simply a software skill, but rather a structured modeling methodology requiring engineering judgment, disciplined setup, and critical interpretation of results.

Despite the growing industrial importance of CAE, teaching CFD and FEA effectively at the undergraduate level remains a demanding educational task. Beyond learning software workflows, students must develop modeling rigor: selecting simplifying assumptions, applying boundary conditions, generating appropriate meshes, evaluating numerical convergence, interpreting results critically, and recognizing limitations caused by uncertainty and incomplete information [1], [2]. These competencies are increasingly relevant for workforce readiness, since industry expects early-career engineers not only to operate simulation tools, but also to justify modeling decisions, communicate risk, and support engineering decisions under real constraints.

A critical component of responsible simulation practice is the explicit treatment of verification and validation (V&V). In professional settings, simulation credibility depends not only on obtaining numerical outputs, but also on assessing whether the computational solution is correct with respect to the mathematical model (verification) and whether the model represents reality with acceptable accuracy for the intended purpose (validation). Standards and guidelines such as ASME V&V 20 provide structured approaches to quantify accuracy inferred from comparisons between computational results and experimental data, highlighting the importance of uncertainty and error sources in CFD and heat transfer simulations [5]. Similarly, the AIAA Guide for the Verification and Validation of CFD Simulations offers terminology and procedures to assess the credibility of CFD modeling and simulation results [6]. These perspectives reinforce the educational value of designing simulation experiences that cultivate critical thinking, methodological discipline, and awareness of modeling uncertainty rather than merely teaching software operation.

From an educational standpoint, active learning and experiential learning have been repeatedly associated with improved engagement and learning outcomes in engineering education. Prince's review identifies broad evidence supporting active learning approaches and their effectiveness in promoting student learning [7]. Experiential learning theory further argues that deep learning develops through cycles of concrete experience, reflective observation, conceptualization, and experimentation, motivating authentic tasks and structured reflection in engineering curricula [8]. Additionally, the CDIO framework emphasizes integrating disciplinary fundamentals with professional skills by developing learners through Conceiving–Designing–Implementing–Operating complex engineering systems, strengthening alignment between university activities and real engineering practice [9]. In this direction, problem-based and project-based learning have been proposed as effective strategies to engage students with realistic, open-ended engineering problems and to promote transferable professional competencies [10].

Within simulation education, project-centered teaching has been proposed as an effective strategy to strengthen student understanding of modeling principles while promoting professional skills. Miner [11] introduced a project-based approach to teaching the finite element method through a structural bracket design exercise, emphasizing theoretical foundations and comparison between numerical predictions and experimental results. Similarly, Zhang [12] integrated a sequence of FEA-based projects into machine component design courses, enabling students to connect analytical calculations with numerical simulations across progressively complex examples. These studies demonstrate the pedagogical value of project-based simulation learning within academic environments.

More broadly, Esche et al. [13] documented the implementation of project-based learning frameworks in mechanical engineering curricula, highlighting improvements in student motivation, teamwork, and integration of engineering fundamentals through comprehensive design projects. While these contributions establish the effectiveness of project-based and simulation-supported instruction, they remain primarily situated within university-controlled settings and rely predominantly on academically defined problems and assessment mechanisms.

In contrast, the present work extends these approaches by embedding sustained industry participation directly into the learning process. Beyond project-based simulation activities, the proposed model incorporates continuous mentoring by practicing engineers, externally informed evaluation criteria aligned with professional review practices, and an industry-facing recognition mechanism. Moreover, students address authentic industrial CFD and FEA problems across two consecutive semesters, enabling exposure to distinct physical domains while working under realistic engineering constraints. This integrated structure provides a replicable framework for translating professional CAE expectations into undergraduate education, bridging the gap between traditional academic simulation exercises and real-world engineering workflows.

Industry-aligned projects add an additional layer of authenticity by incorporating realistic constraints, professional feedback cycles, and evaluation criteria closer to engineering practice. This is particularly relevant because CAE is deeply embedded in industrial workflows across domains such as automotive development, aerospace applications, and process engineering, where both CFD and FEA inform decisions under time, performance, and safety constraints [3], [4]. Consequently, simulation-based educational experiences that reflect industry expectations can strengthen professional communication, increase engagement, and better prepare students for the complexity of real engineering work.

To better contextualize the academic background of the participating students, the curricular sequence leading to the proposed experience is briefly outlined below.

Students are introduced to the Finite Element Method (FEM) and Finite Volume Method (FVM) starting in the sixth semester of the Mechanical Engineering program, initially through analytical foundations and MATLAB-based implementations for simple structural and fluid dynamics problems. In subsequent courses, FEM is progressively applied to basic and intermediate engineering case studies using commercial CAE software. This curricular sequence ensures that, by the time students enroll in the senior elective described in this paper, they already possess foundational modeling skills, allowing the course to focus on engineering judgment and industry-oriented problem solving rather than software training.

This paper presents an industry-supported Numerical Simulation Challenge implemented in a senior-level undergraduate mechanical engineering elective course on computer simulation. The course introduces CFD and FEA modeling methodologies and aims to enable students to solve engineering problems through workflows grounded in the finite volume method and the finite element method, while emphasizing responsible modeling practices and professional engineering reasoning. The challenge is designed as an authentic problem-solving experience in which student teams work in pairs or even individually on an engineering problem proposed by an industry partner and receive mentoring and technical feedback during the project lifecycle. The same student cohort completes a CFD-based challenge in one semester and a FEA-based challenge in the following semester.

The goal of this work is to describe the design and implementation of this Numerical Simulation Challenge and discuss its educational potential to promote student engagement, competence development, and perceived learning in simulation-based engineering practice. By presenting this structured college–industry cooperation experience, this paper contributes to ongoing discussions on how simulation education can be delivered with rigor, responsibility, and relevance while reflecting the authentic complexity of professional engineering environments [7], [9], [10].

The remainder of this paper is organized as follows: the next section describes the course context and the structure of the Numerical Simulation Challenge, including its timeline, deliverables, and evaluation criteria; the subsequent section presents the student perception survey design and summarizes key results; finally, the discussion section highlights lessons learned, limitations, and implications for adopting similar industry-supported simulation challenges in other engineering programs.

METHODOLOGY

The Numerical Simulation Challenge follows a structured pedagogical sequence consisting of problem introduction, guided modeling, independent simulation development, technical reporting, and professional-style evaluation. The challenge is divided into two phases—CFD and FEA numerical simulations—which are implemented during two instructional windows across consecutive semesters. In each phase, three regular classes are dedicated exclusively to the challenge, enabling direct interaction between students and the industry engineer, either in person or remotely depending on professional availability.

During the first session, the engineer introduces the industrial problem, defines simulation parameters, boundary conditions, deliverables, and deadlines, and organizes students into pairs. Approximately four weeks later, a mentoring session is conducted in which each team presents preliminary results, discusses modeling decisions, and receives technical feedback from the engineer. In the final session, held four weeks after the mentoring checkpoint, students submit a complete technical report and formally present their results. The required deliverables and assessment criteria are detailed in subsequent sections. The competencies developed by the students and the corresponding evidence used for evaluation are summarized in Table 1.

Table 1 *– Competencies and evidence*

COMPETENCY	EVIDENCE
Predict the results of problems using simulation	Results of the numerical simulations
Communicate effectively in both oral and written forms.	Report

CFD Numerical Simulations

The first part of the cooperative challenge, as mentioned, was the performance of CFD numerical simulations of equipment provided by the industry. In the last three years the equipment chosen was an emulsifier, as presented in Figure 1 and the simulations were carried out on the ANSYS® Software platform.

***Figure 1**. Industrial emulsifier [14]*

The industry provided the students with simplified CAD (Computer Aided Design) geometry, shown in Figure 2, so they can start the steps of a numerical simulation problem that are: treatment of the geometry, generation of the mesh, setup of the simulation and post-processing.

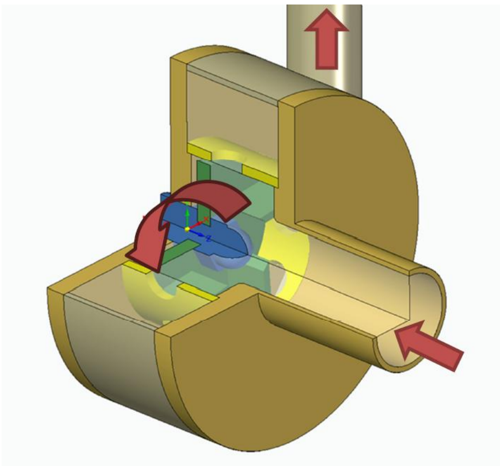


***Figure 2**. CAD geometry of the industrial emulsifier with inflow and outflow indicated by arrows as the rotation direction*

Besides CAD geometry, the industry's engineer also provided the following parameters to be used in the simulations:

- Specific mass of the fluid: 1100 kg/m³
- Fluid viscosity: 2000 cP
- Rotation: 3400 rpm
- Maximum power: 1,5 hp

The parameters that must be measured or calculated in the post-processing phase were also specified:

- Shear rate, in 1/s
- Power consumption, in hp
- Inlet/Outlet pressure, in Pa
- Volume flow, in m³/h

In the report, the students must present, at least, two complete numerical simulations, one with the exact geometry that was given to everybody and the other with a different geometry, designed by them, only for the blades, as it was not allowed to change the geometry provided. The students are stimulated by the engineer to optimize the blades of the equipment and do as many tests as they can. Each of these steps must be documented in a report containing the following information:

- Geometries simulated
- Mesh used in the simulations and its quality parameters
- Setup of the simulation
- Residuals of the numerical solution
- Contours of velocity
- Graphic of outlet pressure
- Contours of pressure

FEA Numerical Simulations

The second phase of the Numerical Simulation Challenge focuses on Finite Element Analysis (FEA), in which students are required to model and evaluate a mechanical system under realistic loading conditions inspired by industrial operation. In this phase, the challenge proposed to the student teams is based on an industrial shaft assembly subjected to combined torsional and bending loads, including key machine elements such as shaft steps, keyways, pulleys, gears, and bearing supports (Figure 3). This choice is representative of common mechanical transmission systems found in industrial machinery and process equipment, where structural integrity and fatigue resistance are critical for reliability.

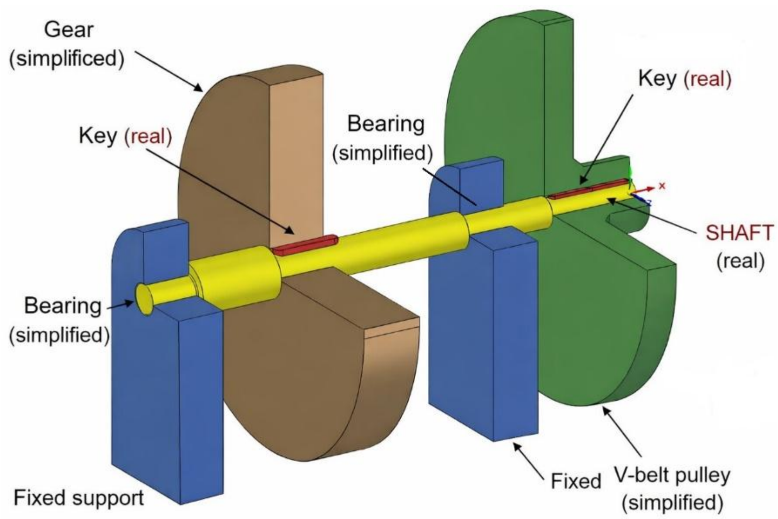


Figure 3. *Simplified shaft assembly used in the FEA Numerical Simulation Challenge, highlighting the shaft, gear, V-belt pulley, bearings, and real keys.*

Following the overall challenge structure, the FEA phase is also supported by an industry engineer through three dedicated class sessions: (i) challenge presentation with design and simulation requirements, (ii) mid-project mentoring and technical alignment, and (iii) final submission and evaluation of the technical reports. In this phase, students must provide technical justification for modeling assumptions and demonstrate simulation credibility through mesh quality evaluation, boundary condition consistency, and critical interpretation of results.

Challenge objectives, constraints, and fixed inputs (industry-aligned requirements)

To increase authenticity and ensure alignment with real engineering expectations, the FEA challenge was defined with explicit objectives and fixed parameters provided by the industry partner. Students were required to evaluate the mechanical integrity of an industrial shaft system (including keyway regions and simplified external elements such as a gear and a V-belt pulley) under realistic load conditions, and to report results using professional engineering criteria (stress, fatigue, and modal performance). The challenge was organized into three scenarios: (i) Scenario #1 – Analytical**,** where students performed manual calculations as a baseline; (ii) Scenario #2 – FEA, following the required case defined in the problem statement; and (iii) Scenario #3 – FEA bonus**,** where students were encouraged to redesign the system to achieve a target safety factor FS = 3.0, by modifying shaft and keyway geometry while maintaining feasibility and engineering justification (Table 2).

A key restriction of the activity was that several material parameters were treated as fixed inputs to maintain consistency across student solutions and allow a fair comparison between teams. The adopted shaft material properties were provided explicitly as: Young's modulus E = 193 GPa**,** Poisson's ratio $\nu = 0.29$**,** yield strength $\sigma_\gamma = 262$ MPa**,** and ultimate tensile strength $\sigma_u = 448$ MPa, under an isotropic, isothermal, static structural modeling assumption. In addition, fatigue performance was addressed using an ASME-based guideline (referred in the challenge statement as "Fatigue ASME"), and the challenge documentation reinforced that "infinite life" should be interpreted as 1×10^6 cycles, establishing a clear quantitative benchmark to guide student durability interpretation.

Table 2. Summary of FEA challenge structure: scenarios, required outputs, and quantitative targets

Scenario / Input	Required?	Expected outputs (report deliverables)	Quantitative targets / fixed values
Scenario #1 – Analytical baseline	Yes	Hand calculations to estimate loads/stresses and support comparison with FEA results	Baseline for validation/consistency check
Scenario #2 – FEA (baseline design)	Yes	von Mises stress, deformation, critical regions, and structural safety discussion	Industry-defined geometry and load case
Scenario #3 – FEA redesign (bonus)	Bonus	Redesigned geometry + simulation evidence + justification of improvements	Target FS = 3.0
Material model (shaft)	Yes	Material assumptions stated explicitly in the report	E = 193 GPa, ν = 0.29, σ_γ = 262 MPa, σ_u = 448 MPa
Fatigue guideline	Yes	Fatigue reasoning documented (criterion and interpretation)	"Fadiga ASME"; infinite life defined as 1×10^6 cycles

The FEA workflow adopted in the course mirrors professional CAE practice and is structured into four main stages: geometry preparation, contact definition, mesh generation, and numerical solution/post-processing. In particular, students are expected to model the assembly interaction by defining appropriate contacts (e.g., bonded, frictionless, or no-separation depending on component interfaces), since the mechanical behavior of shaft systems is strongly influenced by contact conditions between keys, shaft, gear/pulley hubs, and supports (Figure 4).

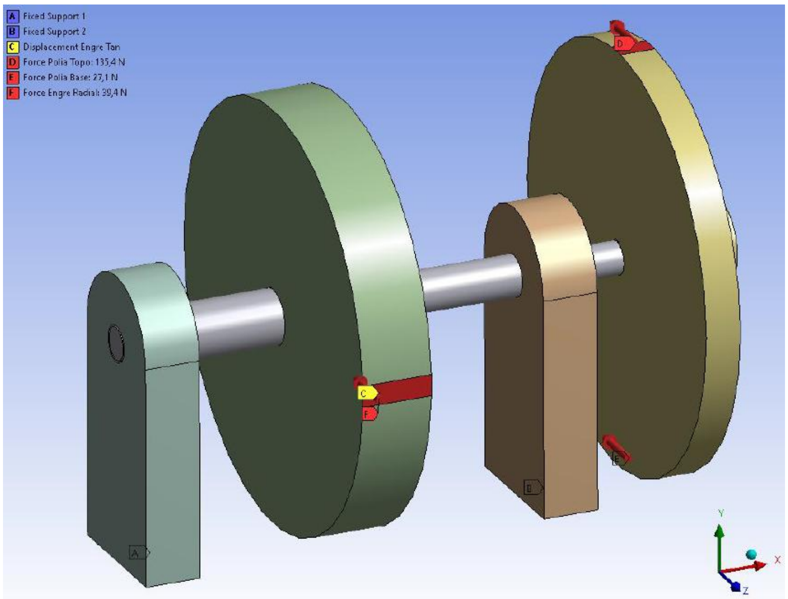
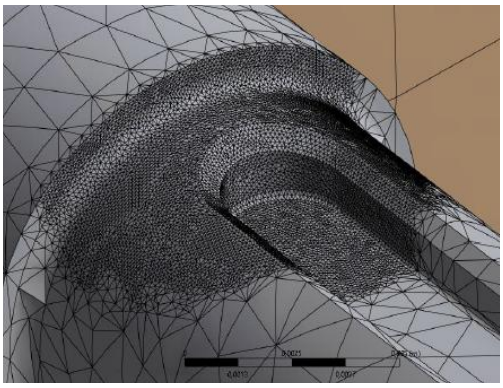


Figure 4. *General boundary conditions.*

Regarding discretization, students generate three-dimensional finite element meshes with local refinements in stress-concentration regions such as keyways, fillets, diameter reductions, and contact interfaces. A key requirement is that the mesh should be accompanied by objective quality indicators (e.g., element quality metrics and refinement strategy documentation) and that the modeling decisions should reflect engineering reasoning rather than purely software-driven choices.

Criteria	Pictorial	Bad	Good	Excellent
Element Quality	Combination of below	0.001-0.10	0.20-0.69	0.95-1.00
Aspect Ratio		>10	10-5	5-0
Warping		>0.4	0.4-0.2/0.1	0.2/0.1-0
Jacobian		>30	30-10	1
Skewness		>0.75	0.75-0.25	0.25-0

(a)



(b)

Figure 5. *(a) Criteria for ANSYS structural solvers. (b) Example of finite element mesh with local refinement.*

The numerical analyses performed in the FEA phase include static structural evaluation (displacements and von Mises stress distribution), safety factor assessment, and, when applicable, fatigue estimation and modal analysis. The fatigue component supports discussions about durability and reliability for rotating shaft systems under cyclic loading conditions, while the modal analysis component is included to verify whether natural frequencies are sufficiently separated from the operational excitation range, which is a common design concern in rotating machinery and transmission systems.

Finally, similar to the CFD challenge, the FEA technical report requires students to document their modeling workflow, justify decisions under realistic constraints, and propose design improvements based on simulation evidence. The reports are evaluated using structured criteria aligned with professional review practices, emphasizing not only numerical results but also modeling coherence, interpretation quality, and feasibility of engineering recommendations.

Evaluation Method – Academic and Industrial Performance

To enhance the assessment of student performance, a more quantitative and less subjective evaluation methodology was established. During the first session of the challenge, all assessment criteria are presented to the students, together with the rationale underlying their adoption.

Essentially, the methodology, presented by the industry's engineer, seeks to reproduce the real corporate environment within the university setting, thereby increasing students' chances of success during the early years of their professional careers.

	Valid?	Copy?	Cases	First Evaluation	Writing Formatting	Mesh	Setup	Results	Conclusion	ShearRate [1/s]	Power [HP]	Pressure [Pa]	Flow [m³/h]	Academic Performance	Industrial Performance	Final Score	Status	Presents?
Group 1	Yes	No	3	10,0	9,0	7,0	9,0	8,0	9,0	0	0,160	0	3,68	8,7	10,0	9,1	Approved	#3 Place
Group 2	Yes	No	3	10,0	7,0	8,0	7,0	6,0	6,0	0	-	0	0,00	7,3	4,0	6,2	Approved	
Group 3	Yes	No	3	10,0	7,0	6,0	7,0	7,0	6,0	0	0,100	0	5,26	7,2	6,0	6,8	Approved	
Group 4	Yes	No	3	10,0	7,0	9,0	8,0	8,0	2,0	0	0,163	0	3,89	7,3	10,0	8,2	Approved	
Group 5	Yes	No	3	10,0	10,0	10,0	9,0	9,0	9,0	0	0,172	39.000	4,35	9,5	10,0	9,7	Approved	#1 Place
Group 6	Yes	No	1	10,0	6,0	9,0	9,0	6,0	4,0	0	-	0	0,00	7,3	4,0	6,2	Approved	
Group 7	No	No	1	0,0	5,0	7,0	7,0	4,0	0,0	0	-	0	0,00	3,8	0,0	2,6	Failed	
Group 8	No	No	1	0,0	5,0	8,0	7,0	4,0	0,0	0	-	0	0,00	4,0	0,0	2,7	Failed	
Group 9	Yes	No	3	10,0	10,0	10,0	9,0	9,0	10,0	261	0,161	0	3,71	9,7	9,0	9,4	Approved	#2 Place
Group 10	Yes	No	2	10,0	7,0	8,0	8,0	7,0	6,0	0	-	0	4,54	7,7	6,0	7,1	Approved	
Group 11	Yes	No	2	10,0	8,0	9,0	8,0	8,0	9,0	0	0,230	0	5,04	8,7	9,0	8,8	Approved	
x	x	x	3,00	x	7,4	8,3	8,0	6,9	5,5	261	0,160	39.000	5,26	7,4	6,2	7,0		
x	x	x	Highest	x	Average					Highest	Lowest	Highest	Highest	Average	Average	Average		

Figure 6. *Table of assessment for the reports. The numbers are illustrative, just to show how the table works*

As illustrated in Figure 6, each rubric criterion is evaluated numerically.

Each criterion is scored on a 0–10 scale, where 0 indicates the item is missing or technically incorrect, 5 indicates an acceptable response meeting minimum expectation, and 10 indicates excellent execution supported by clear evidence. Intermediate scores reflect partial fulfillment and/or limited supporting evidence.

For reference, the 0–10 scoring scale is approximately aligned with the conventional A–F grading system commonly used in U.S. higher education, where scores of 9–10 correspond to an A level (excellent), 8–8.9 to B (good), around 7 to C (satisfactory), around 6 to D (minimum passing), and below 6 to F (unsatisfactory). This mapping is provided solely to aid interpretation and does not represent a formal grade conversion.

Final grades are assigned individually or per team, depending on whether students elect to work alone or in pairs, and are based exclusively on the submitted technical report evaluated by academic and industry reviewers using the defined rubric.

These grades are subsequently used to rank projects and identify the teams invited to present their results to industry engineers.

The evaluation criteria, that was developed mainly by the engineer with help from the teachers, are divided into the following sections:

1. Verification of Valid Participation (blue columns)

A comparison among reports is conducted to verify whether any form of academic dishonesty has occurred. This includes searching for similarities across one or more reports, such as identical language patterns, numerical results, photographs, and tables. In several cases, identical critical errors have already been identified.

There is also a verification process to determine whether students actually achieved an engineering-based result or merely supplemented the report with fabricated data or with the use of artificial intelligence (an unauthorized resource).

From the beginning of the challenge, students are explicitly instructed not to engage in such practices, as they are senior engineering students who must understand and adhere to principles of ethics and professional conduct.

It is also consistently emphasized that, in a real corporate environment, similar practices would likely result in dismissal or even legal action.

2. Academic Evaluation (yellow columns)

Students are assessed on whether they demonstrate skills compatible with the engineering profession, such as appropriate formal technical language; the ability to systematically present hypotheses and validation methods; proficiency in executing the numerical simulation setup as taught in previous classes; and the ability to extract from the obtained data a logical, plausible, coherent, and robust conclusion.

3. Industrial Evaluation (green columns)

The mathematical results are extracted from each student's report and compared against a reference model that has been previously executed and physically validated.

4. Scoring (pink columns)

A simple arithmetic average is calculated for each performance category (academic and industrial). Access to these data is restricted to the instructors and the senior engineer.

5. Award (red column)

A weighted average of the scores is calculated, with the academic component assigned a weight of 2 and the industrial component a weight of 1. The three highest-scoring students receive an award and present their reports to the class.

After the delivery of the report and the presentation, the students answered a survey to measure their perception about engaging in an industry-academia project during their undergraduate course. It is important to point out that this survey only evaluated their perceptions about engaging in the activity and has limitations such as biased answers based on their performance in the activity, for example.

The questions were:

Question 1 – Did you find interesting to solve a real applied problem within your Mechanical Engineering Course? Yes, No, Indifferent

Question 2 – Do you think that solve a real problem, proposed by an industry, contributed to improve your knowledge in numerical simulation? Yes, No, Indifferent

Question 3 – Would you have enjoyed engaging in more projects like this throughout the course? Yes, No, Indifferent

RESULTS

In this section, one presents the results of numerical simulations obtained by one of the groups, to illustrate what was expected from the students and the results of the survey answered by them.

CFD Numerical Simulations

In the first section of the report, the students should have presented the geometries simulated, including the one that is common for everybody. In Figure 7, it is shown, on the left, the CAD provided by the industry and, on the right, the set of different geometries developed by one group.

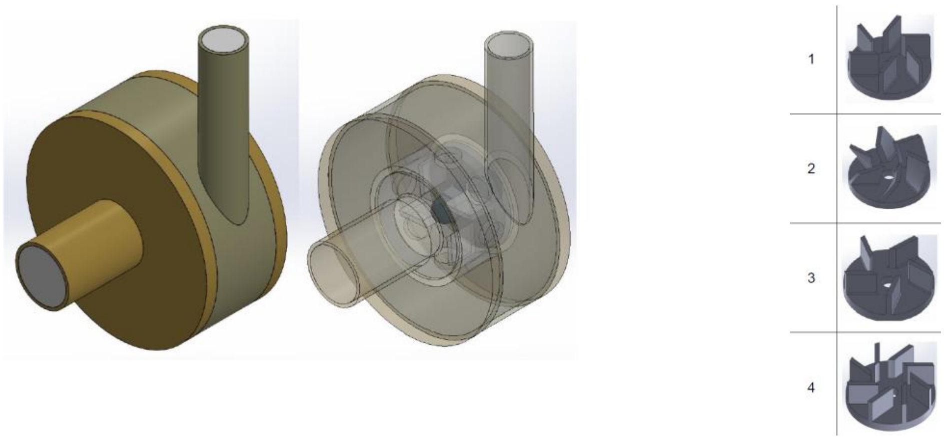


***Figure** 7. Original CAD Geometry on the left and set of different geometries developed by the students on the right*

On the next section of the student's report, they present details of the mesh used in the simulations as well as at least one quality parameter. In Figure 8, on the left, the mesh is presented and, on the right, the skewness of the elements

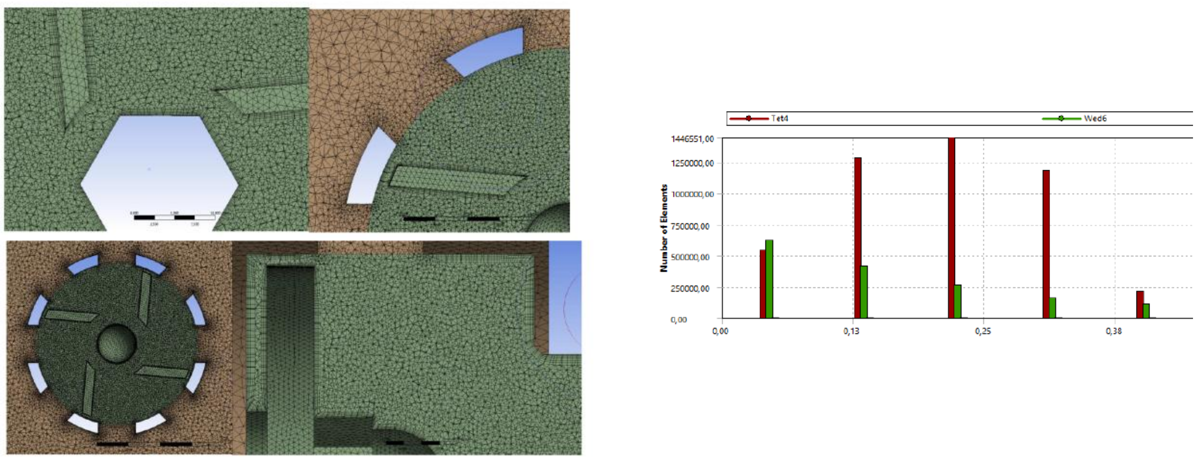


***Figure 8**. Details of the rotor mesh on the left and skewness distribution on the right*

Continuing the report, the students provide all the information used during the setup phase such as fluid and operations parameters as well as boundary conditions and solver properties. To show that the simulation converged with the setup developed by them, they presented the residuals of the numerical simulation, as shown in Figure 9

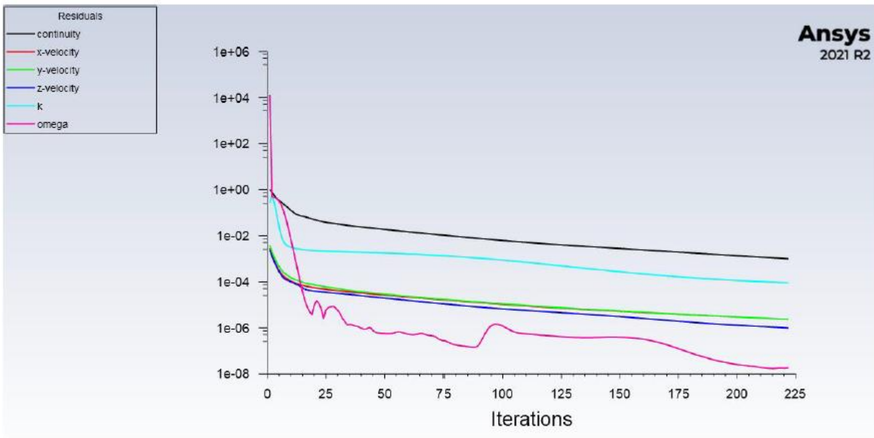


***Figure 9**. Residuals of the numerical simulation*

At this stage, the results must be presented containing, as mentioned: contours of velocity, graphic of outlet pressure, contours of pressure and the calculation of shear rate, volume flow and power. In Figure 10 both contours of pressure and velocity are shown and in Figure 11, the outlet pressure graphic is presented.

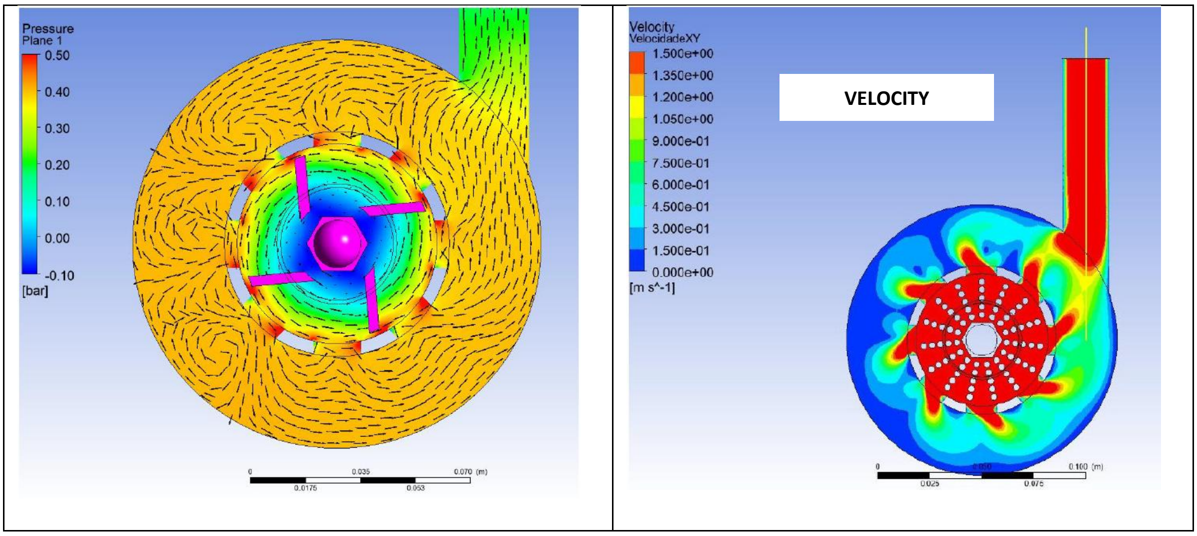


***Figure 10**. Contours of pressure on the left and contours of velocity on the right*

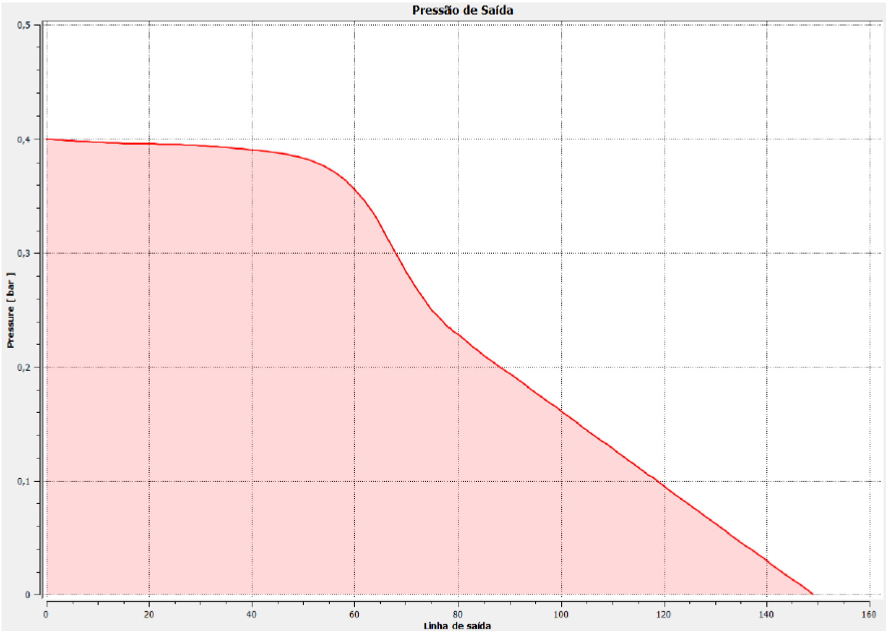


Figure 11. *Outlet pressure*

FEA Numerical Simulations

To illustrate the expected outcomes of the FEA Numerical Simulation Challenge, this section summarizes representative results obtained by student teams whose reports were evaluated as excellent. The selected examples demonstrate the type of engineering reasoning students were expected to develop, including interpretation of stress concentration regions, mesh refinement decisions, and structural safety verification through complementary criteria such as von Mises stress distribution, fatigue assessment, and modal response.

In the FEA challenge, one of the key learning goals is to highlight how geometric discontinuities and functional design features—such as keyways, shaft diameter transitions, and contact interfaces—directly influence the stress field and the potential onset of failure mechanisms. Student reports consistently identified keyway regions as critical locations due to their role as stress concentrators, which aligns with classical design practice and reinforces the importance of refining the mesh locally in these regions to obtain reliable peak stress values. For example, in one representative case, the effective equivalent von Mises stress components used for fatigue reasoning reached $\sigma'_a = 68.08$ MPa and $\sigma'_m = 61.57$ MPa in a critical section (Section C), while another region (Section D) exhibited a higher mean equivalent stress value of $\sigma'_m = 100.80$ MPa, reinforcing the presence of critical zones requiring engineering attention (Figure 12).

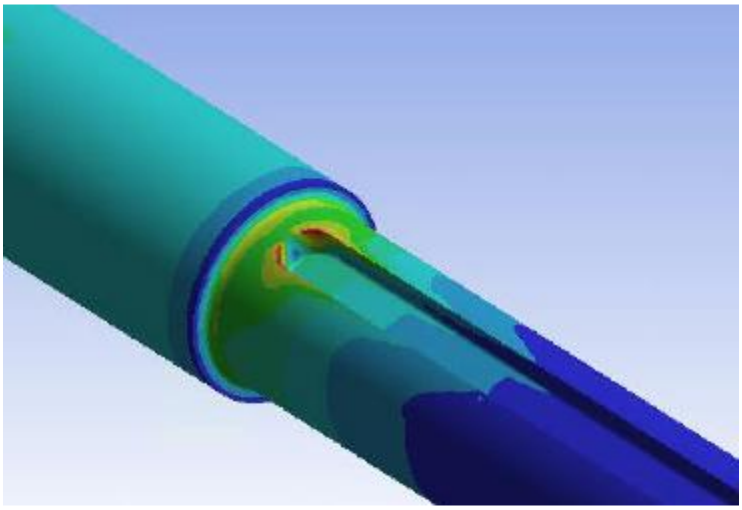


Figure 12. *Representative case of the effective equivalent von Mises stress in a critical section (Section C).*

A representative student workflow began with analytical calculations to estimate internal loads and preliminary sizing, followed by the finite element modeling of the complete shaft assembly. In the model setup, student teams applied realistic boundary conditions by constraining bearing supports and applying external loads associated with gear and pulley forces. This allowed them to compute displacement fields and equivalent stress distributions for the full system, providing a clear visualization of critical zones and enabling structured engineering interpretation of the results.

In addition to stress distribution, the evaluation criteria required students to quantify structural adequacy through safety factor metrics and fatigue-related checks. For instance, in a representative report, fatigue safety factors computed using the Goodman criterion were n_{fb} = 4.90, n_{fc} = 1.72, and n_{fd} = 4.44, revealing that one shaft section (Section C) presented the lowest fatigue margin and would likely govern the redesign effort. In another example, the Goodman-based fatigue safety factor for a critical section was also estimated as n_{fc} = 1.85, supporting a consistent interpretation that fatigue considerations can become the limiting factor even when static stresses may appear acceptable.

A distinctive element of the challenge is that students were encouraged to propose design improvements grounded in simulation evidence. In one representative redesign iteration, students modified shaft diameters in multiple regions, for example increasing Section B from 17 mm to 20 mm, and Section E from 22 mm to 25 mm, in order to improve stress and fatigue margins while maintaining feasible manufacturability. Beyond dimensional changes, students also adopted geometric strategies to reduce stress concentration effects, such as the "sled runner keyway" approach applied to the end of the keyway slot, illustrating how simulation results guided practical design decisions.

Modal analysis results were also used as part of the engineering validation reasoning. In one case, students computed the shaft operational excitation frequency from the rotation speed of 1725 rpm, corresponding to 28.75 Hz, and compared it against the first natural frequency obtained from modal simulation. The first vibration mode was reported as 85.94 Hz, indicating sufficient separation from the operational frequency and thus low resonance risk. Additional modal results documented higher natural frequencies such as 280.97 Hz, 286.5 Hz, and 430.44 Hz, reinforcing that the analyzed design remained outside critical resonance conditions across multiple modes.

Overall, these representative results demonstrate that the FEA Numerical Simulation Challenge moves beyond software training by requiring students to interpret outcomes critically, identify limiting design aspects, propose feasible improvements, and defend engineering decisions based on numerical evidence. This aligns with the industry perspective that FEA supports structural optimization, reliability improvement, and failure mitigation in real engineering contexts.

From an educational perspective, these results indicate that students progressed from procedural software use toward integrated engineering reasoning, demonstrating improved ability to identify governing failure mechanisms, justify modeling decisions, and translate numerical outputs into design actions. Compared to early project stages, final reports showed clearer technical argumentation, improved documentation quality, and more consistent linkage between simulation evidence and engineering recommendations.

Students's performance

It is noticeable that, at the beginning of the academic year, many students still carry a mindset focused solely on obtaining grades and passing university courses, often without a clear perception of the technical and legal responsibility they will face once they become engineers in the job market.

Throughout the academic year, a continuous effort is made to raise awareness, motivation, and appreciation of the calculations performed, emphasizing how these analyses directly impact the lives of real people as well as the operational safety of real industrial and corporate environments.

On the last day of class, a review and discussion of the main shortcomings observed during the development of the projects are conducted, issues that are not acceptable in a corporate environment. It is also emphasized that such failures could lead to serious consequences in professional practice, including dismissal or loss of credibility with company management, which would inevitably hinder salary progression and access to positions of greater responsibility and trust.

As a result of this process, students complete the course not only having had their first contact with high-level numerical technologies, such as FEA and CFD, but also with a significant improvement in their ability to write clear and objective technical conclusions for managers and decision-makers. In addition, they develop greater critical judgment when interpreting visually appealing software-generated results, learning to question and validate them through practical and physics-based analysis.

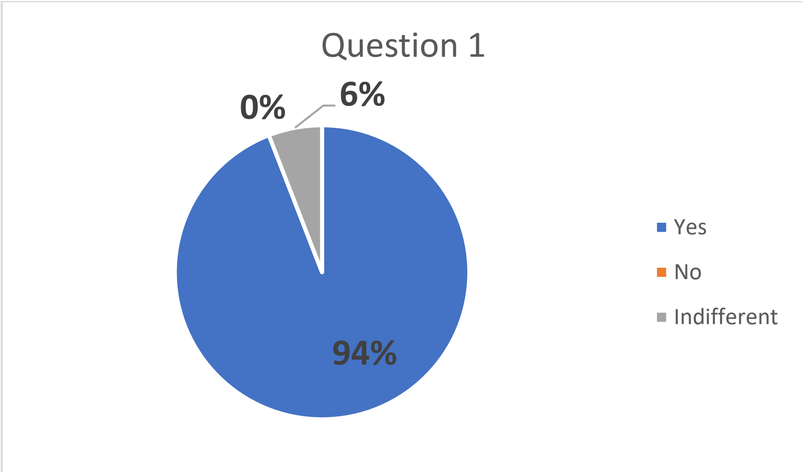
Basic errors, such as inappropriate language, illegible figures, lack of bibliographic references, absence of benchmarking, among others, are identified and addressed at different stages of the project development. In professional practice, these aspects often translate into concise presentations with few slides, supported by solid technical content, coherent narrative, and clear communication.

Unfortunately, every year there is a small percentage of students who drop out or abandon the projects, submitting reports that are extremely poor and unacceptable. In these cases, a face-to-face and individualized approach is adopted to identify the reasons behind this behavior and, whenever possible, attempt to reverse the situation.

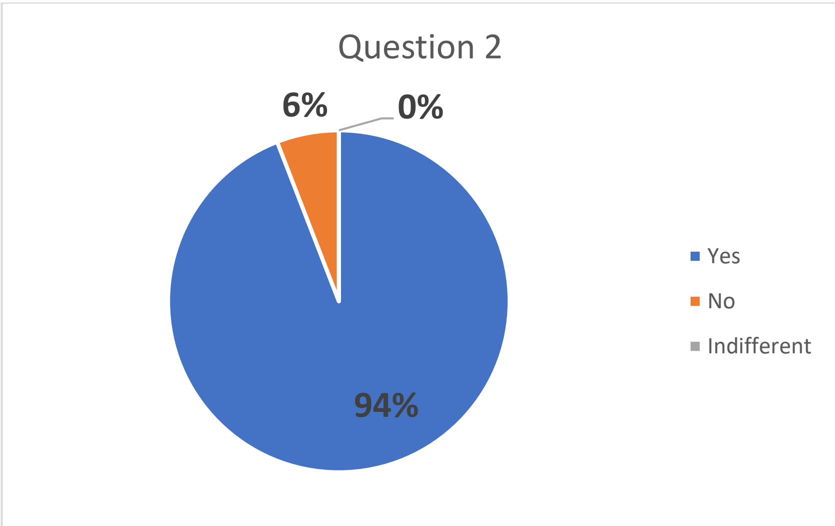
With each new edition of this discipline, treated as a formative challenge, there is a consistent improvement in student engagement rates, as well as increased motivation toward STEM topics that, in previous years, had lower levels of acceptance.

After presenting their work, the students answered the survey presented on the "Methodology" section and the results, considering all the answers since the challenge is being applied, are show below. The survey was answered by 40 students among 80 that took the course. Again, it is important to point out that these results only show the perception of the students about this activity they took part in.

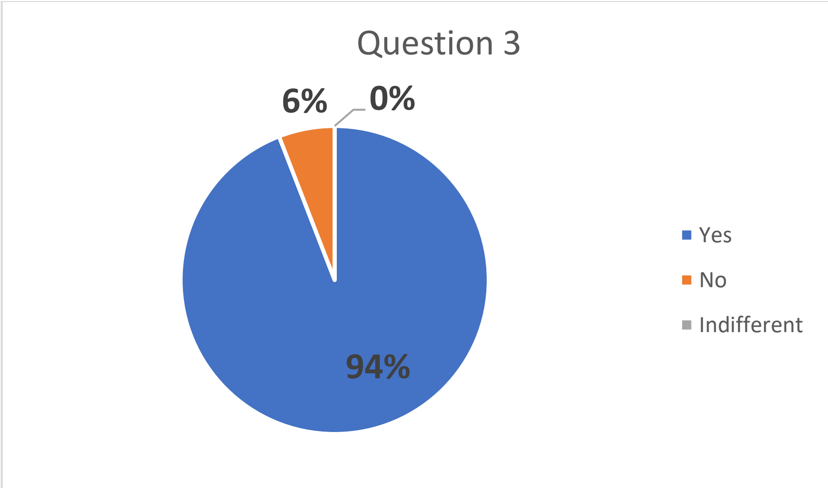
Question 1 – Did you find interesting to solve a real applied problem within your Mechanical Engineering Course?



Question 2 – Do you think that solve a real problem, proposed by an industry, contributed to improve your knowledge in numerical simulation?



Question 3 – Would you have enjoyed engaging in more projects like this throughout the course?



FINAL CONSIDERATIONS

This paper presented an industry-supported Numerical Simulation Challenge implemented in a senior-level mechanical engineering elective course focused on CAE tools, integrating both CFD and FEA problem-solving experiences across different course offerings. The challenge was designed to expose undergraduate students to realistic engineering constraints, industry mentoring cycles, and professional-style evaluation criteria, strengthening the connection between academic simulation training and industrial expectations.

The experience reported in this paper aligns with prior literature demonstrating the educational value of project-based simulation activities in mechanical engineering courses [10]–[12]. Previous studies have shown that integrating FEA projects into academic settings enhances conceptual understanding and student engagement. The present work builds upon these foundations by incorporating sustained industry mentoring, externally informed evaluation criteria, and authentic industrial constraints within a structured CFD and FEA learning sequence.

The consistently high level of positive student perception observed over four years (88% reporting improved learning of CAE tools) suggests that embedding real industrial participation may further strengthen both engagement and professional readiness. By combining project-based learning with industry interaction, this model provides a replicable framework for aligning simulation education with professional engineering practice while maintaining academic rigor.

The proposed model contributes not only to the development of technical competencies in CFD and FEA workflows, but also to essential professional skills such as engineering judgment, critical interpretation of results, documentation quality, and decision justification. In the FEA phase, for instance, students were required to combine multiple layers of analysis—such as contact modeling, stress concentration identification, fatigue reasoning, and modal evaluation—highlighting that simulation competence is strengthened when students engage in integrated engineering interpretation rather than isolated software procedures.

From an instructional perspective, one of the main strengths of the challenge is its replicable structure, supported by a sequence of industry-participation checkpoints, well-defined deliverables, and assessment criteria that reflect professional review practices. This framework helps students understand that simulation credibility depends on the coherence of assumptions, boundary conditions, mesh strategy, and interpretation quality, reinforcing responsible modeling practices and alignment with engineering decision-making requirements.

In addition to academic outcomes, the industry-supported challenge also presented relevant professional and career-oriented benefits for participating students. Across course offerings, the industry partner has shown continued interest in identifying high-performing teams, including requesting student résumés for potential recruitment and employment interviews. This reinforces that the proposed framework not only enhances technical learning, but also increases student visibility and strengthens workforce readiness by creating direct connections with industry expectations.

Another distinctive element of the experience is the external recognition component associated with the final evaluation. The top-performing teams receive formal certificates jointly issued by the university and the industry partner, which students often report as a meaningful differentiation when pursuing internship opportunities. This recognition mechanism contributes to motivation and engagement by adding authenticity and professional relevance to the simulation deliverables, while also encouraging students to demonstrate higher levels of commitment, rigor, and communication quality.

As future work, the authors recommend strengthening the systematic integration of verification and validation principles within the challenge, including explicit convergence checks, uncertainty awareness, and reference comparisons whenever feasible. Additionally, future implementations may explore enhanced collaboration outcomes such as expanding mentoring frequency, incorporating experimental validation opportunities, and developing internship pathways to further connect academic simulation learning with industry needs.

In conclusion, this work contributes to engineering education discussions by offering a structured and sustainable model for integrating industry mentoring and authentic CAE deliverables into undergraduate simulation education. By combining real-world engineering problems, professional evaluation criteria, and external recognition, the Numerical Simulation Challenge supports student engagement, develops professional-level simulation competencies, and strengthens the transition from academic learning to engineering practice.

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