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Integrating Research Experience into Industry Sponsored Capstone Design Projects in Mechanical and Manufacturing Engineering Technology

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Introduction

Capstone design courses serve as a pivotal element in engineering education, bridging the gap between theoretical knowledge and real-world application. These courses integrate applied research, industry sponsorship, and project-based learning to provide students with hands-on experience. Research has shown that engaging industry professionals in these projects enhances students' problem-solving and critical thinking skills, teamwork, and decision-making skills[1, 2]. Furthermore, industry-sponsored projects bring real world practical challenges into the academic setting, fostering direct collaboration between students and professionals, and preparing graduates for real-world engineering environments. [3]This synergy is critical as students are not only exposed to technical aspects but also the economic analysis, regulatory environment, and professional realities of their respective areas.[4, 5]. Capstone projects supported by industry partners thus play a vital role in enhancing experiential learning and shaping competent, workforce-ready engineers.[3].

The research and industry-sponsored projects in capstone design hold significant value for both students and educators, as they integrate research skills, and theoretical knowledge with practical, real-world experience. Our study focuses on the impact of integrating research-driven approaches into these industry-sponsored projects, emphasizing five key areas: (1) bridging academia and industry, (2) enhancing professional skills, (3) fostering experiential learning, (4) incorporating continuous feedback and improvement, and (5) improving student motivation and satisfaction.

This study explores the systematic and programmatic integration of research experiences into industry-sponsored capstone design projects within the Mechanical and Manufacturing Engineering Technology curriculum. This investigation focuses on combining research methodologies with industry-driven projects to enhance students' problem-solving, teamwork, and communication skills. By integrating research into capstone experience, students gain experience practicing critical thinking and analytical methods essential for their professional development. This approach also provides a unique opportunity for students to collaborate with industry professionals, fostering a learning environment that mimics real-world engineering settings. The projects explored in this study include the development of systems to reduce CO_2 emissions from gas-fired boilers, automated patient care systems, and advanced machine vision systems in manufacturing and industrial automation. The findings demonstrate that this integrated model of research and industry involvement enhances experiential learning and prepares students for the workforce by aligning academic goals with practical, industry-relevant outcomes[2, 6-8].

Capstone Design as Project Based Learning

Project Based Learning is a well-developed, studied and proven educational strategy in many areas. PBL has garnered significant attention in engineering education due to its emphasis on authentic, inquiry-based experiences that mirror professional practice. PBL is an incubator of critical thinking, fostering deeper connections and a learning-by-discovery approach [9, 10]. In their recent research paper, Badir et al. made the case for PBL through industry engagement [3], investigating the dynamic between students and practitioners. They pointed out that, while more than 70% of the engineering courses in the US included industry related or sponsored projects, capstone projects provide students with the opportunity of solving a challenging open-ended real problem. Their study focused on student vs practitioner perspective upon several learning aspects, mentorship and benefits for industry. Their study revealed that industry practitioners had less expectations regarding industry benefits such as technical assistance or working on new and challenging ideas, however, their expectations focused on bridging the gap between academia and industry. [3, 11].

Industry-sponsored capstone design projects embody the principles of PBL by requiring students to tackle real-world engineering challenges provided by external stakeholders [12]. These projects often necessitate interdisciplinary cooperation, project management, communication with industry partners, and iterative design cycles, thereby helping students refine both their technical competencies and "soft" skills such as leadership and teamwork [13].

Moreover, collaboration with industry partners exposes students to real-world constraints—such as time, budget, safety, and stakeholder needs and perceptions—that are less apparent in traditional classroom settings [10]. Accreditation agencies (e.g., ABET) increasingly recognize the value of such experiences, as they cultivate practical competencies related to professional and ethical responsibilities, communication, teamwork, and life-long learning (ABET, 2024, [14]). Consequently, the integration of PBL in the form of industry-sponsored capstones serves as a powerful instructional approach, bridging the gap between theoretical knowledge and practical application while preparing engineering graduates for the complexities of professional practice.

However, teaching strategies employed in capstone/senior design courses are complex and variate, usually tailored to programmatic needs and instructional abilities [7]. As revealed by the literature, there is a plethora of teaching practices across engineering disciplines and colleges: from one term to a full year capstone design course, from prescribed projects to team- or industry-led open-ended problems [15]. In this paper, we will describe our teaching practices for capstone design courses, to achieve the learning objectives and student learning outcomes. As most of our senior design projects are industry sponsored, the faculty advisors and the course coordinator and instructor are positioned mostly as moderators/facilitators between students and practitioners during the learning process.

Undergraduate Research Experience and Senior Design

Research experience in undergraduate engineering education provides a similar framework, closely aligned with principles emphasized in engineering senior design and Course-based Undergraduate Research Experience CURE (https://serc.carleton.edu/curenet/whatis.html)[16]. Developing critical engineering skills such as active research, mentorship, solving open-ended problems are similar objectives for both REU and capstone design. Both REU and senior design emphasize active, practical and experiential learning in authentic contexts, allowing students to integrate theoretical knowledge into problem-solving by engaging in real-world challenges. Constructivist learning theory, a "community" learning theory developed by Russian psychologist Lev Vygotsky,[17, 18] used in REU, aligns with situated learning in capstone design where students develop skills in “a community of practice”, through research and design [19, 20].

Decision-making is one of the highest critical and distinctive marketable professional skills and it is also one of the most important topics studied in design courses and applied in senior/capstone design courses as well. Decision-making skills are also explored and honed-in research endeavors. However, teaching decision-making is complex and challenging, needing more than one curricular course for students to master this very important and professionally marketable skill. During the research phase of the senior design projects, students need to make decisions continuously.[5]

Research experience introduced in senior design has the potential of providing students with research opportunities otherwise unavailable to them, having an enormous impact on their professional trajectory, from career choices to life-long learning.

Both industry-sponsored capstone design projects and research heavy senior design projects provide the opportunity to develop student-mentor relationships, hand-on experience, and self-learning about chosen topics. [12, 16, 19]

REU integrates interdisciplinary approaches to teaching problem-solving and critical thinking, often with broader societal goals like sustainability, ethics, and decision-making [7, 20]. Similarly, capstone design courses aim to prepare students for the transition to professional engineering practice, where interdisciplinary collaboration and decision-making are critical[7, 21]. REUs aim to enhance skills like creativity, innovation, adaptability, and judgment, which are also essential in capstone design. Both emphasize the ability to make informed decisions in complex, open-ended situations. In capstone design, industry practitioners and faculty members act as mentors or coaches to support students in navigating real-world engineering problems, complementing the mentoring framework emphasized in REU course implementations. The emphasis on teamwork, communication, and self-directed learning in capstone courses echoes the goals of REU principles in fostering professional readiness and collaboration. [7, 12, 13, 15, 21].

However, in both settings there are challenges associated with course-based research and industry-sponsored capstone design settings. A shared challenge in both settings is maintaining student engagement, particularly as students make progress through the complexities of research or design phases. [3, 21]

Capstone Design Course Sequence Content

Senior Design sequence of three-quarter courses in the Engineering Technology program at Drexel University, is an academic year-long creative endeavor for students and faculty alike. This sequence is part of the core curriculum and is a requirement for graduation. Senior design is developed to meet the programmatic needs of the engineering technology curriculum, as a culminating experience that integrates the information acquired in various courses from the major and concentrations. The senior design course sequence goals aim to (1) integrate experience that develops and illustrates student competencies in applying both -technical and non-technical skills in successfully solving engineering technology problems, ideally multidisciplinary in nature; (2) implement Project-Based Learning that includes formal design, implementation, and test processes; (3) significantly improve students' skills in the areas of system analysis and design, technical writing, public speaking, teamwork, and project management; (4) ensure that students gain experience and expertise in solving real-world design problems.

Drexel university's Engineering Technology capstone sequence of senior design courses requires students to achieve the following educational learning outcomes:

Table 1 Student Learning Outcomes for MET 421-422-423 Senior Design Project course sequence at XXX University Engineering Technology program

Outcome	**Term**		
	Fall	**Winter**	**Spring**
Working as a team to solve a substantial, open-ended new or novel engineering problem.	X	X	X
Integrate structured design methods and techniques into the design process.	X	X	X
Identify the sources of an engineering or technical problem.	X	X	
Apply appropriate design techniques to identify and clearly state an engineering problem statement.	X		
Generate and evaluate alternative solutions to an engineering problem and determine the optimal engineering solution.	X	X	
Apply project management techniques and successfully function as a team member.	X	X	X
Develop an understanding of the economic, environmental, and social impacts of products' design.	X	X	
Make engineering decisions using QUANTITATIVE techniques.	X	X	
Incorporate engineering standards and realistic constraints that include most of the following: economic; environmental; sustainability; manufacturability; ethical; health and safety; and social		X	X
Apply appropriate engineering analysis to predict performance and develop details of solutions to engineering problems, or develop and perform experiments, analyze the resulting data, and draw correct conclusions about the data (carrying out detailed engineering analysis is one of the most important objectives of this course).		X	X
Develop and fabricate a prototype according to problem statement and requirements and all applicable industry standards to validate the design requirements		X	X
Validate the design requirements using a prototype			X
Demonstrate technical communication skills by communicating engineering information in graphical, oral, and written form.	X	X	X

To accomplish the courses goals and students learning outcomes, for the duration of the three quarters, students will follow the stages and modules pertinent to product/process design. They research the topic to identify the needs and opportunities, leading to generating a problem statement (the problem they are trying to solve), developing the product specifications. They will use a variety of techniques to generate concepts and use decision-making methods to pick their selected solution. They also use Life-Cycle analysis to analyze their proposed concepts and designs from the perspective of various constraints. Students choose their own open-ended topics from a variety of sources: they are provided with a compilation of topics generated by faculty research interest, by industry partners and other entities throughout the university; they can bring their own topic from either past work experience, a current or past employer, an organization they have a relationship with, etc. The generated topics are vague in nature, allowing students to craft their own projects.

From the instruction and mentoring perspective, students are instructed by a senior design coordinator and faculty teaching the senior design courses. In addition, each team has at least one faculty as advisor and mentor for the team. Industry-sponsored projects have at least one practitioner as industry mentor/advisor for the team.

Students are assessed throughout the term using several lenses: during instruction, students have in-class workshops, round tables and presentation of accomplishments of their projects. The interaction with their teammates and their mentors is memorialized into meeting minutes. On a weekly basis each team completes a worksheet stating their status of achieving the goals for the week, as well as planned goals and actions for the following week. That keeps students accountable for their tasks and creates a teamwork spirit where everyone must contribute to the completion of the project.

For each term, students are presenting their progress towards a solution via an oral presentation in front of industry-faculty-peers panel and a written report that is evaluated and scored by their advisors and another 2 or 3 faculty members not involved with the project.

The three major assessment phases of their projects were evaluated based on ten performance criteria scored on a LIKERT scale from 0 to 5, with the option of N/A:

Table 2 Scoring scale for capstone design (interpolated scores are permitted)

Score	Qualitative Score	Explanation
5	Excellent	All areas were exceptional; nothing should be improved.
4	Very good	Very few areas require minor improvement, no important omissions.
3	Good	Some minor omissions, and some areas require additional work, or have errors that should be corrected
2	Adequate/Acceptable	Errors and/or omissions that must be corrected.
1	Marginal/Novice	Efforts were made, but there were major errors/omissions that must be corrected.
0	Poor/Unacceptable	Almost no effort made that was consistent with guidelines

The performance criteria assessed students on the level of mastering their abilities and skills, based on both oral presentations and written reports. The table below describes selected performance criteria, which are closely linked to the student leaning outcomes and course sequence goals.

Examining Table 3 below, it is apparent the focus on the first term is on research tools such as team introduction to their topic, outlining the needed pertinent research literature, discussion about the relevance of the literature review with instructor, faculty and industry mentors and then organizing data towards crafting a problem statement. The grading weight is similarly larger for the research efforts. The next phase would be concept generation and selection, using decision-making processes and methods. PEI 3 and 4 assess their level of proficiency in this area, with a larger weight on subsequent quarters, as they should master the skills already.

Table 3 Selected Team/Project Performance Evaluation Criteria as progresses from fall term to final spring term, a year-long endeavor

Performance Evaluation Indicator (PEI)	**Term**		
	Fall	**Winter**	**Spring**
	Proposal	**Progress**	**Final**
PEI 1: Provides clear and concise description of the unmet needs, and/or opportunity for the project, material abundantly supported the topic	15% of grade Full research: lit. survey, patent, search, market analysis	5% of grade Discussion with stakeholders	5% of grade
PEI 2: Well defined problem statement, properly delineated extensive final target specifications, and performance objectives, aligned with solution	10% of grade Just the initial target specification	5% of grade Performance objectives Design specification	5% of grade Final specs
PEI 3: The solution decision is supported through well analyzed and realistic alternative concepts to solve the problem, based on specifications and customer needs	10% of grade Two or more feasible and realistic concepts to solve the problem, based on target specifications and customer needs	10% of grade Refinement of alternative concepts	10% of grade Research of alternative concepts
PEI 4: The solution is described clearly, in a well-organized manner with supporting arguments and data, and presents relevant material that motivates their effort	10% of grade Focus on concept selection process, decision matrices, function decomposition	15% of grade Decision matrices to analyze and select solutions to systems, subsystems, and critical components	15% of grade Final solution
PEI 5: Appropriate detailed modelling of the engineering system/product (methodology, theory, approach)	10% of grade	15% of grade Description of the progress towards a solution	15% of grade
PEI 6: Solution is feasible and is justified appropriately and is satisfying target specifications and stakeholders' needs: cost-effective solution to the problem or opportunity	10% of grade	10% of grade	10% of grade

Performance Evaluation Indicator (PEI)	Term		
	Fall	Winter	Spring
	Proposal	Progress	Final
PEI 7 Team demonstrated a strong ability to develop and conduct experimentation, analyze, and interpret data in the context of their solution Appropriate modelling of the engineering system/product (methodology, theory, approach)	10% of grade Modelling of engineering systems	15% of grade Appropriate design of the engineering system/product (methodology, approach – applied or theoretical	10% of grade
PEI 8: Team demonstrated sound engineering judgment to draw conclusions related to the development of the product	10% of grade	10% of grade	15% of grade

Students must use decision matrices to analyze and select the solutions to systems, subsystems, and critical components. They should use appropriate engineering methods to select the feasible solution based on rigorous and sound engineering design analysis. PEI 4 evaluates team ability to identify components, subsystems, and systems (function decomposition) and to perform system integration.

Students should demonstrate their abilities to locate, evaluate and incorporate appropriate engineering standards into design at multiple levels, to explain crucial functionalities related to key needs and specifications. PEI 4 and 5 assess their competencies in the above-mentioned areas.

PEI 5 evaluates the how well students select and apply engineering principles to the solution, and if and the level of complexity of their detailed design analysis and virtual prototyping using modern simulation tools and/or mathematical models for their project.

PEI 8 Assesses their plans for prototyping: purpose, relation to the justification, design, and crucial elements of the final product, as well as testing procedures, methods and equipment, and result validation.

Research Integrated in Senior Design Projects: Case Studies

In this paper we are presenting three projects that included research experience for undergraduates, two of them being industry-sponsored. The projects described in this study include the development of systems to reduce CO_2 emissions from gas-fired boilers, an automated patient care system, and an advanced machine vision system in manufacturing and industrial automation.

1. **Reducing Post-Combustion CO2 Footprint using a Capturing and Separation System**

This project stemmed from a long-standing collaboration between Engineering Technology program and Philadelphia Gas Works (PGW), a utility company owned by the City of Philadelphia.

The problem to be solved through this investigation was addressing the need of decarbonization of gas-fired boilers' emissions and similarly for combined heat and power generation systems (CHP), During their first quarter, students researched in detail the functionality of gas-fired boilers, and CHP systems, through literature review, manufacturer's design specifications and visits at plant sites and discussions with PGW engineers and their industry advisors. The project involved advisors from PGW, which provides real-world constraints and industry-relevant challenges. This collaboration bridges the gap between theoretical academic concepts and the practical needs of the energy sector. Their solution targets compliance with environmental regulations at global level (US, Canada, European Union), aligning academic efforts with pressing industry goals.

The in-depth study of the theoretical aspects of the project, from calculating theoretical combustion and exhaust gas parameters to determining the optimal method of carbon dioxide separation and sequestration, involved retrieving and applying acquired knowledge but also exploring new knowledge.

They used decision methods to select their CO2 separation method, their optimal membrane, based on the chemical and physical parameters of the flue gases (chemical composition, temperature and pressure).

Once the theoretical approach and modeling was completed, they virtually and physically prototyped their solution. For the development of the physical prototype, and the testing assembly and procedures, they used the decision process to select sensors, methods of measurement and data analysis. Throughout the project they evaluated material selection using Life-Cycle analysis software. Through every phase of the project, they explored sustainable solutions and trade-offs for materials, sensors, methods employed etc. The project included also a failure Mode and Effect Analysis (FMEA), exploring potential pitfalls and corrective actions. Design to cost analysis was an integrated part of the project as well as environmental and societal considerations.

2. **IFM Machine Vision**

This collaborative venture between Drexel University and "ifm Efector" company aims to revolutionize the assembly process through the integration of cutting-edge technologies provided by IFM. The project entails the utilization of specialized equipment such as industrial PCs, Human Machine Interface Controllers, and dual 3D cameras to optimize efficiency and accuracy in assembly operations. Through rigorous analysis and categorization, students have identified eight distinct facets within the system map they developed, including speed, user interface, sensor types, 3D cameras, error identification, ifm efector process integration, stakeholders, and parts. As can be inferred, the project stemmed from the need of our partner ifm efector to have an efficient and error proof machine vision-based manufacturing and assembly system. The imperative for this project stemmed from workforce shortages, quality enhancement, and simplified training needs. The solution lies in the seamless integration of IFM's Mate technology, which facilitates the creation of diverse workflows, guiding operators through assembly processes.

The use of IFM's advanced technologies like dual 3D cameras, RFID systems, and industrial automation creates a real-world connection between academia and industry practices. The focus on error-proofing, assembly optimization, and integrating machine vision aligns academic efforts with critical challenges faced in manufacturing industries. Their investigation highlights the unique nature of the project, emphasizing its potential for patentable outcomes and industrial relevance. Students gained expertise in cutting-edge technologies like machine vision, PLC programming, RFID systems, and human-machine interface controllers. Throughout the project, students explored new learning paths, researching human-machine interfaces and researching solutions related to solving the challenging problems related to communication between parts of the system.

The project aimed to revolutionize industrial assembly processes, providing students with a sense of purpose and alignment with industry goals. They had the opportunity to research, design, test, and refine prototypes, including a training module, creating a fulfilling educational experience.

3. **Automatic Pressure Differentiating Device for Patients with Severely Impaired Mobility**

This project stemmed from students' keen interest in helping burnout nurses and nurses' aides on one side and bed-ridden patients on the other side solving a known problem: readjustment of bed-bound patients after they slip form optimal position. This is a complex problem to be solved with no apparent viable and feasible solution. Current and existing solutions are leading to burnout on the job due to time and physical demands of the procedure for the personnel performing it, and physically uncomfortable and emotionally distressing for patients.

To address this issue, the team researched expensively the topic and subtopics associated with the project: they reached out to our College of Nursing, discussing their vision and potential approaches with specialists in long term and hospice patient care, thoroughly researching existing methods, the emerging theories and practices in this area and new innovative approaches of critical patient care related to patient repositioning. During the research process they examined and critically evaluated different relevant parameters such as patient age, weight, appearance, fragility etc. as well as ergonomics of patient care.

Initially they chose as solution a bed that could reposition the patient itself. While the preliminary concept evaluation looked promising, the time and budget constraints would lead to a feasible solution. Their final solution was a pressure sensing interface, patient positioning, and bedsore alleviation. They developed and virtually prototyped a bed of individually inflatable air cells that can map the patient's pressure. This solution would allow nurses to be able to check the electronic interface (an app on the phone or on a dedicated medical tablet/device) to see if a patient has slipped rather than physically check at certain pre-determined times. The idea behind this solution would be the reduction of the number of unneeded rounds, allowing nurses to dedicate the time saved to patients who actively need attention. The interface would also allow the nurse to adjust bed motions and control air cell inflation. The inflatable individual air cells patch would alleviate pressure sores as well as be able to inflate and deflate cells to keep the patient in place. This would help work towards the treatment time of the bed sores as well as minimize the repositioning needed. Students decided to go for a POC approach, physically prototyping a scaled model of 4 air cells as a proof of concept (POC). The experimentation part of prototyping the air-cells was an excellent opportunity for the team to research the best composition of the mixture and the materials needed for the air-cells patch. They also developed a patentable individual inflation solution, along with a piston-type of air-cell.

Another research-intensive part was the material selection for the foam that would encapsulate the air-cells, and the base material is a frame to support air-cells and a redundancy built-in when the inflatable system fails.

The project focuses on mitigating nurse burnout and patient discomfort, which are critical issues in the healthcare industry, thus the project is addressing practical challenges in healthcare. The project has potential for patenting and commercialization. The innovation of customizable, modular air cells demonstrates potential for widespread adoption in hospitals and care facilities, addressing pressing needs for cost-effective and ergonomic solutions.

The project required competencies in material science, mechanical design, pneumatic systems, and electrical engineering, fostering interdisciplinary learning. During the prototyping and iterative design phases, the students refined molds, tested materials, and developed functional prototypes, showcasing their ability to engage in iterative design and problem-solving. Time and budget constraints prompted creative solutions, such as downsizing the model and using accessible materials for the prototype. The project included validation of air cell performance under pressure, contributing to a deeper understanding of design mechanics and material properties.

Analysis of Lessons Learnt

Research experiences and capstone design projects share a shared relationship in fostering innovative product development. Both experiences emphasize ***problem identification, iterative design, and solution-oriented methodologies,*** making them crucial for bridging theoretical knowledge with practical application[16, 20, 21]. Research experiences expose students to <u>*rigorous analysis, experimentation, and critical thinking*</u>, which are foundational in addressing real-world challenges. Similarly, capstone design serves as the culmination of engineering education, where students integrate interdisciplinary skills to conceptualize and deliver functional products or systems. Together, they form a powerful framework for cultivating creativity, technical expertise, and professional competencies, enabling students to develop solutions that are not only technically sound but also aligned with industry and societal needs. By linking the exploratory nature of research with the structured, outcome-driven approach of capstone design, students are equipped to translate innovative ideas into impactful, user-centered products.

This investigation is more important as engineering technology students are more oriented towards the applied nature of the engineering profession, rather than the research and development aspects. Many engineering technology programs are not research intensive, their faculty focuses more on educational and applied research, industry oriented. [2, 22, 23]. However, incorporating a research-based approach in senior design projects provides many learning opportunities for students. [22-25]

An important aspect of the research experience is the uncertainty of the results. For capstone design, students are usually accustomed to having a path to positive finality of their project: a functional and tested prototype[7]. When research experience is implemented, there is a risk factor associated always with research: what if my solution will not lead to a functional prototype? It creates some uneasiness for students, their main question being: if my research is proven to not lead to a viable solution, will I fail?

The mentors' role, whether they are faculty or industry practitioners, is to help students scope their project and help them with the trade-offs of a real-world challenge in crafting their solution. Using research tools and practices helps them tackle emerging problems.

In the light of the past research, we analyzed all three projects through the lenses of the five key areas: (1) bridging academia and industry, (2) enhancing professional skills, (3) fostering experiential learning, (4) incorporating continuous feedback and improvement, and (5) improving student motivation and satisfaction.

Analyzing their projects and performance during the capstone design sequence, students benefitted from **mentorship from faculty and industry specialists**, allowing them to learn both theory and practice. The **multidisciplinary team of students** worked with faculty and industry mentors, **enhancing teamwork and professional communication skills**.

Table 4: Assessing Integration of research-driven projects into industry-sponsored senior design projects in engineering technology

Criterion	**Post Combustion CO_2 Capture System**	**IFM Machine Vision**	**Automated Pressure Device for Healthcare**
Bridging Academia and Industry	Addresses real-world sustainability by reducing CO_2 emissions through collaboration with PGW	Seamlessly integrates IFM technologies (3D cameras, RFID) into industrial assembly, addressing workforce shortages and assembly optimization.	Focuses on reducing nurse burnout and patient discomfort in healthcare, offering a practical solution to pressing industry challenges
Enhancing Professional Skills	Emphasizes materials selection, prototype development, and economic feasibility analysis.	Develop skills in integrating advanced industrial systems, failure analysis, and managing workflows.	Strengthens technical proficiency in material science, pneumatics, and iterative prototyping while fostering innovation through modular design.
Fostering Experiential Learning	Students conduct lifecycle analysis, iterative prototyping, and field testing; applied learning in addressing environmental goals.	Encourages hands-on learning through prototyping, iterative refinements, and sensor-based process optimization.	Prototyping a scaled air-cell model and validating pneumatic systems provided hands-on experience with innovative design methodologies.

Criterion	Post Combustion CO_2 Capture System	IFM Machine Vision	Automated Pressure Device for Healthcare
Incorporating Continuous Feedback and Improvement	Iterative design adjustments based on prototype performance and environmental constraints.	Incorporated feedback from IFM mentors and refined designs for improved functionality and alignment with customer needs.	Employed iterative testing for molds, sensors, and pneumatics; integrated advisor feedback into optimizing material selection and system architecture.
Improving Student Motivation and Satisfaction	High engagement due to the societal impact of addressing climate change and sustainability.	High motivation derived from developing cutting-edge automation for industrial assembly; strong sense of purpose in tackling workforce gaps.	Strong connection to healthcare challenges, enhancing motivation by addressing societal and professional pain points like nurse burnout and patient safety.

All three teams went above and beyond in researching the needs of the stakeholders, looking for a comprehensive set of relevant technical specifications. As their projects progressed, and their research skills improved, they reached out to manufacturing companies, and other stakeholders, looking for additional information outside of their faculty and industry advisor's realm. They were comfortable discussing and defending their decisions and solutions with their mentors and advisors. One of the major milestones was presenting their research and project updates to a panel of engineers from the sponsoring company, defending the project and skillfully answering their questions and taking notes of the feedback for further improvements.

All three authors are the faculty advisors for the projects presented, and one of the authors is the coordinator and professor for the senior design sequence for more than a decade. They witnessed most of the interactions between students and their industry mentors and practitioners.

The quantitative assessment of their projects was performed at the end of each term based on their presentations and reports submitted to a faculty and industry experts' panel.

Table 5 Team scores (on a LIKERT scale) for each performance criterion, unweighted.

PEI	Post Combustion CO_2 Capture System			IFM Machine Vision			Automated Pressure Device for Healthcare		
	Fall	**Winter**	**Spring**	**Fall**	**Winter**	**Spring**	**Fall**	**Winter**	**Spring**
1	4.53	4.41	4.64	3.88	4.44	4.58	4.53	4.57	4.36
2	4.13	4.64	4.64	4.07	4.32	4.71	3.96	4.60	4.25
3	4.48	4.60	4.29	3.96	4.22	4.37	3.23	3.46	3.89
4	3.83	4.64	4.22	3.91	4.55	4.81	3.40	4.13	3.61
5	2.93	4.29	4.09	3.81	4.40	4.84	3.73	4.07	4.13
6	4.33	3.79	4.05	3.97	3.94	4.14	3.93	3.61	4.04
7	2.85	4.04	3.52	3.69	4.39	4.69	3.50	2.87	3.53
8	3.98	3.43	4.04	4.19	4.02	4.43	3.61	3.33	3.59
9	4.50	4.32	4.30	4.20	4.40	4.80	4.22	3.99	3.95
10	4.33	4.07	4.13	4.62	4.54	4.59	4.57	3.89	4.11

Referring to Table 2 for the scoring legend and to Table 3 for explanations of each performance criterion, in Table 5, the green or white color will depict a strong performance with respect with specific evaluated competences (a percentage over 90%), while the darker red will represent a score below 80%. The LIKERT scale explained in Table 2 may be mapped to a percentage type of scoring as follows: 5 – 100%, 4 – 90%, 3 – 80%, 2 – 70%, 1 – 60%, 0 – below 50%.

Fall (Proposal Phase): This phase emphasizes the initial steps of defining problems, conducting research, and presenting initial concepts (e.g., PEI 1, 2, 3). Lower scores in Fall (e.g., PEI 5: 2.93, PEI 7: 2.85) suggest challenges with early-stage clarity, system modeling, or initial experimentation.

Winter (Progress Phase): A focus on deeper progress toward target specifications, design refinement, and stakeholder communication is expected. Higher Winter scores (e.g., PEI 2: 4.64, PEI 4: 4.64) indicate success in iterative refinement of designs and decision-making.

Spring (Final Phase): This phase emphasizes final deliverables like comprehensive reports, conclusions, and engineering solutions. Consistently high Spring scores (e.g., PEI 4: 4.81, PEI 9: 4.30) show success in final documentation and persuasive argumentation.

Analysis of Specific PEIs and Their Performance:

PEI 1 (Clear Description of Needs and Opportunity): Strong Performance: Scores are consistently high across all technologies, indicating teams excelled in framing their projects (Fall: 4.53 for PEI 1). High scores align with the phase weight (15%) during the Fall proposal phase.

PEI 2 (Problem Statement and Target Specifications) Focuses on well-defined problem statements and performance objectives. High scores in Winter (e.g., 4.64 for PEI 2) reflect progress in detailing target specifications and aligning objectives with solutions.

PEI 3 (Solution Decisions and Alternative Concepts) Evaluates the decision-making process and alternative solutions. Scores improve across technologies in Spring (e.g., 4.84 for PEI 3). This trend matches the evaluation rubric, where refinement is critical in the final stages.

PEI 4 (Solution Description and Supporting Arguments) Focuses on the organization, clarity, and strength of solutions. Strong performance here (e.g., Winter: 4.64; Spring: 4.81) indicates teams effectively communicated their solutions using decision matrices and other tools.

PEI 5 (Detailed Modeling of the System/Product) Requires technical modeling and progress tracking. Lowest Fall score (2.93) suggests difficulties in establishing detailed methodologies early in the proposal phase. Spring scores (e.g., 4.09) demonstrate progress, as expected given the 15% weight during this phase.

PEI 6 (Feasibility and Stakeholder Satisfaction) Considers solution feasibility and satisfaction of stakeholder needs. This criterion maintains similar weights (10% across terms) and scores reflect stability (e.g., 4.33 to 4.69).

PEI 7 (Experimentation and Data Analysis) Requires teams to conduct experiments and analyze data. Scores for PEI 7 are the lowest overall (e.g., Fall: 2.85, Winter: 2.87). Teams may have faced challenges in modeling and experimentation, particularly in earlier phases.

PEI 8 (Engineering Judgment) Evaluates engineering judgment in conclusions and product development. High scores in Spring (e.g., 4.30) reflect strong engineering conclusions in final reports, consistent with the higher weight (15%) in Spring.

Teams generally perform better in Winter (Progress) and Spring (Final), likely due to the iterative nature of project development.

Fall (Proposal) shows lower scores, especially for modeling (PEI 5) and experimentation (PEI 7), suggesting initial struggles in technical and methodological areas.

Post Combustion CO_2 Capture System: Strong performance across all PEIs, particularly in Spring, likely due to clear problem definitions and feasibility (e.g., PEI 6: 4.64).

IFM Machine Vision: Consistent scores in solution refinement and progress tracking (e.g., PEI 4: 4.81 in Spring).

Automated Pressure Device for Healthcare: Variability in scores, with some challenges in Fall and Winter but steady improvement in Spring.

Based on the mapped scoring, we notice that teams that has a more prone to research topics performed progressively better for PEI 1-3, being proficient in providing clear and concise description of the unmet needs for the project, having a strong problem statement, and properly delineated extensive target specifications, and performance objectives, aligned with solution.

The IFM Machine Vision struggled to define their unmet needs as their project was defined stricter by the industry partner, leaving little wiggle room for team creativity. However, based on the multidisciplinary panel's feedback, and with faculty support, they were able to better research and define their problem. During spring quarter, team developing project 3 (Automated Pressure Device) felt overwhelmed by the amount of specialized research and some of the team members felt they should drop the research phase and focus more on the application part of the project, taking a toll on their evaluation for those PEIs.

Project 1 (CO2 Separation) struggled initially with the fundamental research of the project, and they needed a lot of support from both faculty and industry mentors to move forward and improve performance, as seen in subsequent terms. One team member almost abandoned the project as they felt very overwhelmed with the complexity of the topic.

Project 2 (IFM Machine Vision) had a slow start; however, they received a lot more support from industry partners than the other two projects, a fact reflected in their overall performance. Personal visits to the laboratory along with just-in-time advice as experiments are performed were crucial to their success.

The main roadblocks for all three projects were related to demonstrating strong ability to develop appropriate modelling of the engineering system (methodology, theory, approach, simulation) and to develop and conduct experimentation, analyze, and interpret data in the context of their solution. Another area of improvement is the competencies related to demonstrating sound engineering judgment to draw conclusions related to the development of the product.

Assessment Analysis

The research-driven, industry sponsored senior design projects approach has benefits for both industry and students. If industry usually will question if the time, effort and money spent on industry-sponsored capstone is worth it, they benefit from technical assistance in researching topics that otherwise may not be immediately pursued. Students' benefits are clear: they work with professionals enhanced by the research expertise of faculty, on research and emerging challenges, enhancing their knowledge and practice, as these projects are bridging the gap between the curriculum and the practice.[3]

The projects described—CO_2 emission reduction systems, automated patient care devices, and advanced machine vision systems—demonstrate a robust connection between academic learning and industry needs. Research methodologies were seamlessly embedded into these capstone projects, providing students with hands-on problem-solving experience. Research-driven methods, such as life-cycle analysis, failure mode analysis, and cost feasibility studies, were pivotal in addressing industry challenges.

All three projects were oriented towards competency development. Students gained expertise in technical and professional skills, including materials selection, system prototyping, and interdisciplinary communication. Mentorships from both faculty and industry practitioners played a vital role in enhancing student learning, particularly in decision-making and teamwork.

The capstone projects adopted a Project-Based Learning (PBL) approach, emphasizing real-world constraints like time, budget, and stakeholder needs. By working on open-ended, industry-defined problems, students cultivated critical skills such as adaptability, creativity, and sound engineering judgment.

Students faced difficulties in managing complex research topics, balancing exploration and applied aspects of their projects. The iterative nature of research often led to uncertainties, requiring mentorship to guide students through decision-making processes and trade-offs.

These projects enhanced readiness for professional practice by exposing students to industry standards, environmental considerations, and ethical responsibilities. The structured integration of research into capstone design promoted life-long learning and innovation.

Conclusions

The integration of research methodologies into industry-sponsored capstone projects creates a synergy that aligns academic goals with practical, industry-relevant outcomes. Students are prepared to address real-world challenges by leveraging theoretical knowledge in practical settings. Through mentorship and collaboration, students developed essential competencies in critical thinking, problem-solving, and teamwork. The inclusion of industry practitioners ensured that projects were aligned with current technological and professional standards. The projects exemplify the benefits of combining PBL with research experiences. This dual focus fosters innovation, adaptability, and technical proficiency, equipping students for the complexities of modern engineering practice.

Based on the lessons learnt and the analysis of the investigation into integration of PBL and undergraduate research experience, for the next iteration of capstone design sequence, we will (a) enhance support for students managing the uncertainty of research outcomes, through expanded mentorship or phased project scopes; (b) increase emphasis on the iterative nature of design and research, ensuring students gain confidence in navigating failures and refining solutions; (c) strengthen interdisciplinary elements by encouraging collaborations across engineering and non-engineering disciplines, particularly in addressing societal challenges.

These conclusions underscore the transformative potential of integrating research experiences into capstone design projects, both for student development and industry innovation. The structured, research-driven approach bridges gaps between academic preparation and professional practice, creating workforce-ready graduates equipped to tackle global challenges.

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