From Monodisciplinary to Interdisciplinary Learning: A Case Study in the Norwegian Bachelor's Engineering Program by Introducing Systems Engineering Fundamentals

Jamal Safi
University of South-Eastern Norway, Kongsberg
Jamal.Safi@usn.no

Haytham B. Ali
University of South-Eastern Norway, Kongsberg
Haytham.Ali@usn.no

Gerrit Muller
University of South-Eastern Norway, Kongsberg
Gerrit.Muller@usn.no

Introduction

Today's industry problems are increasingly complex and interconnected, requiring solutions that draw upon multiple engineering disciplines. Industrial engineering teams in contemporary settings often operate within an interdisciplinary system development environment. However, the typical university education model usually focuses on monodisciplinary engineers. As a result, while students may gain in-depth knowledge in their specific discipline, they may lack the terminology, methods, tools, and techniques, as well as the skills and shared understanding necessary to collaborate effectively within an interdisciplinary team. In other words, this mismatch presents challenges when undergraduates begin working in the industry.

This paper proposes a solution to bridge the gap between industry and academia: teaching all undergraduate engineering students about Systems Engineering (SE) fundamentals, enriched with practical experience and a case study. SE is widely recognized as the best practice for developing and realizing complex systems, especially in the Norwegian high-tech industry in Kongsberg (INCOSE and Wiley, 2015). SE facilitates the design and engineering of systems by interdisciplinary teams through various methods, techniques, and tools. Our work's significant contribution is its focus on having students practice SE concepts on a specific case.

The authors have been teaching SE to undergraduate students since 2008, even before it became mandatory by the national Norwegian education plan in 2011 (Nasjonalt råd for teknologisk utdanning (NRT), 2011). The course "Systems Design and Engineering" introduces students to key SE concepts, such as systems, system context, and selected toolkits. The authors then guide students in applying these concepts to a real engineering case, allowing them to experience their practical use firsthand. Additionally, the course prepares students for work-integrated learning within their bachelor's and master's programs at USN. In the bachelor's capstone project, students apply what they have learned from the course to solve real-world problems provided by the local industry. The same department also offers an industry master's program in SE, focusing on industrial and executive roles. This unique program allows students to maintain part-time employment (50%) while pursuing their master's degree.

The course incorporates a range of instructional activities, including interactive lectures and hands-on project work. Students are divided into teams of 4-7 undergraduates from mechanical, electronic, and software engineering disciplines. These teams work on a case study applying SE. The instructors present a traditional linear stepwise SE process known as the V-model (INCOSE and Wiley, 2015), while also introducing a more agile and iterative SE framework called the CAFCR (Customer objectives, Application, Functional, Conceptualization, and Realization) model (Muller, 2004).

The instructors use the CAFCR framework to guide students through predesigned lab activities. These activities include identifying stakeholders' needs and requirements, engaging in conceptual design and modeling, defining system requirements, and envisioning a conceptual solution. To facilitate these activities, the instructors employ various techniques such as visualization, iteration, time-boxing, early quantification, and zoom-in and zoom-out (Muller, 2004). This paper advocates integrating SE into the undergraduate engineering curriculum to familiarize students with SE, its interdisciplinary nature, and its practical applications. We believe this will equip students with the necessary skills to function effectively in inherently interdisciplinary team settings within the industry. The course structure aligns with Work-Integrated Learning (WIL) principles through industry collaboration and stimulating real-case applications, aiming to bridge academic preparation with industrial practice. As a supplementary initiative, we regularly invite one to two industry guest lecturers to share real-world SE-related experiences. These sessions are intended to offer students exposure to practices and system-level thinking. While students often express appreciation for these sessions, we acknowledge that the value of such sessions can vary depending on the lecturers' capability to reach students and alignment with their needs and course content.

Theoretical foundation

Industry and academia acknowledge the need for interdisciplinary engineering graduates (Nair and Patil, 2008). Chettiparamb (2007) provides a comprehensive literature review. This review offers a thorough overview of the concept, including its definitions, implications for teaching, potential challenges, and real-world examples. Li et al. define interdisciplinary as "integrating information, data, techniques, tools, perspectives, concepts and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems beyond the scope of a single discipline" (Li et al., 2015). This paper defines interdisciplinary team as the integration and collaboration of multiple engineering disciplines to address complex problems and develop viable technical solutions.

While interdisciplinary collaboration is essential, it presents several challenges for students and educators. One central issue is the deeply rooted disciplinary socialization process that shapes how students think, communicate, and solve problems (Chettiparamb, 2007). Overcoming these established perspectives requires intentional exposure to alternative viewpoints and structured reflection. Students must learn to cope with ambiguity, negotiate shared understanding, and develop a systems perspective that goes beyond their individual discipline. Addressing these challenges requires educational strategies that go beyond knowledge acquisition and focus on identity development, meta-cognition, and communication across discipline boundaries (Fleming et al., 2023).

Interdisciplinary teamwork skills, including effective communication, leadership, conflict resolution, and problem-solving from multiple perspectives, are highly valued in engineering (Pazos et al., 2020). These skills are emphasized by ABET (Accreditation Board for Engineering and Technology) criteria (2025-2026) ("Criteria for Accrediting Engineering Programs, 2025 - 2026 - ABET," 2025). Recent research has further underscored the importance of these skills in engineering (Wisniewski, 2018).

Lattuca et al. (2017) concluded that interdisciplinary engineering skills significantly contribute to students' success in the industry where they work within diverse engineering teams. Their study suggests that introducing concepts such as systems thinking and real-world engineering context enhances the development of the student's interdisciplinary skills (Lattuca et al., 2017). In response to these insights, many institutions have adopted varied strategies for interdisciplinary teaching to prepare students for their future professional careers. For instance, Li et al. (2015) have introduced "Introduction to Design" course, which brings together students from engineering and architecture disciplines and guides them through an integrated design process (Brezing and Löwer, 2008; Li et al., 2015).

Similarly, Ghannam proposes a hybrid module combining Team-Based Learning (TBL) with Problem-Based Learning (PrBL), enhancing students' interdisciplinary SE knowledge and interpersonal skills through technology-driven challenges (Ghannam and Chan, 2023). Another innovative interdisciplinary course, "Conducting Robots," bridges the gap between engineering, science, and the arts, fostering critical thinking, creative problem-solving, and computational thinking.

This paper proposes integrating SE fundamentals into the undergraduate curriculum to foster an interdisciplinary teamwork environment. Moreover, the paper advocates for a teaching approach that combines PrBL, TBL, and Project-Based Learning (PBL). By engaging in instructional activities mapped onto the SE process, teams develop their interdisciplinary skills by applying them to real-world cases.

Results: Case study

The course sets the stage by introducing the fundamentals, concepts, and tools of SE. This includes key concepts such as systems, system context, system hierarchy, and the system life cycle. Additionally, the course covers essential aspects of technical management and group dynamics, highlighting their importance in teamwork. The authors also introduce the students to the V-Model, a widely recognized and practical framework, emphasizing verification and validation at each level (INCOSE and Wiley, 2015). However, a more iterative or agile framework is often needed in a real-industry environment due to short development cycles and rapid design changes (Ali, 2021). In this context, the authors employ the CAFCR+ framework as the foundation for lab activities, guiding students to apply it to a specific engineering case. The CAFCR framework is an agile, iterative, and recursive framework developed by Muller. It includes five views: Customer Objectives, Application, Functional, Conceptual, and Realization. However, Muller also adds the life cycle view as + in CAFCR + (Muller, 2004).

Students work in teams and conduct lab activities. These activities guide the teams in iterating between all CAFCR+ views. Figure 1 visualizes CAFCR+, mapping lab activities to the CAFCR+ views, which helps teams navigate through the different perspectives. The teams conduct four sessions. Each session consists of lab activities that utilize time-boxing, allocating 15 to 30 minutes for each step. Timeboxing ensures that the next step is undertaken once the allocated time has elapsed, even if the previous activity is not yet complete (Muller, 2024).

The authors, as instructors, assist the teams in their lab activities, ensuring they iterate and use timeboxing. In addition to instructor support, an external assessor from industry evaluates together with the instructors, both individual assignments and group-based lab activities, ensuring that the course assessment reflects relevance to real-world practice. Due to simplicity and space limitations, Figure 1 illustrates only the first session. The successive sessions facilitate iterations where teams revisit the CAFCR views multiple times, enhancing the quality of their system solutions as their knowledge and understanding of the problem and solution deepen with each iteration. Figure 1 also shows the structure of the first session. The authors begin with 45 minutes of SE theory, complemented by relevant case examples to keep students engaged. The remaining four hours are dedicated to laboratory sessions for executing engineering and design activities.

During the lab activities, the authors instruct the teams to use flip charts and post-its for sketching and visualization. The teams attach flip charts to the wall to stimulate discussions and facilitate collaborative and shared understanding. After each session, students perform homework to consolidate their manual sketches, drawings, models, and notes into an electronic format using tools like PowerPoint and Visio. This course is embedded in a broader WIL practice at USN. In the bachelor’s program, students are also allocated to industry placements, reinforcing their exposure to real-world problem-solving. Furthermore, the SE master’s program follows an industry-integrated model where students work 50% in industry and study 50%. This model includes courses such as Reflective Practice, which focuses on developing students’ reflective mindsets and real-world engineering practice. Rather than focusing on applying theoretical tools, the course encourages students to critically examine how their academic experiences influence their thinking and actions in real-world engineering contexts. Together, these components strengthen the academic-industry link and create feedback loops to adapt the course content to evolving industry needs continuously. This continuity is further supported at the doctoral level by a PhD program based on an “industry-as-laboratory” research methodology, where candidates conduct applied research in collaboration with industrial partners. A connected industry research school provides funding and internships specifically for PhD candidates. More broadly, USN at Kongsberg partners also engage in collaborative research projects and engineering programs, including bachelor's theses and master’s theses, which further deepen industry engagement and support knowledge exchange across all levels of engineering education.

Figure 2 shows a team actively participating in the CAFCR lab activities. In 2025, the case involves designing an innovative system to assist elderly people in managing their daily activities.

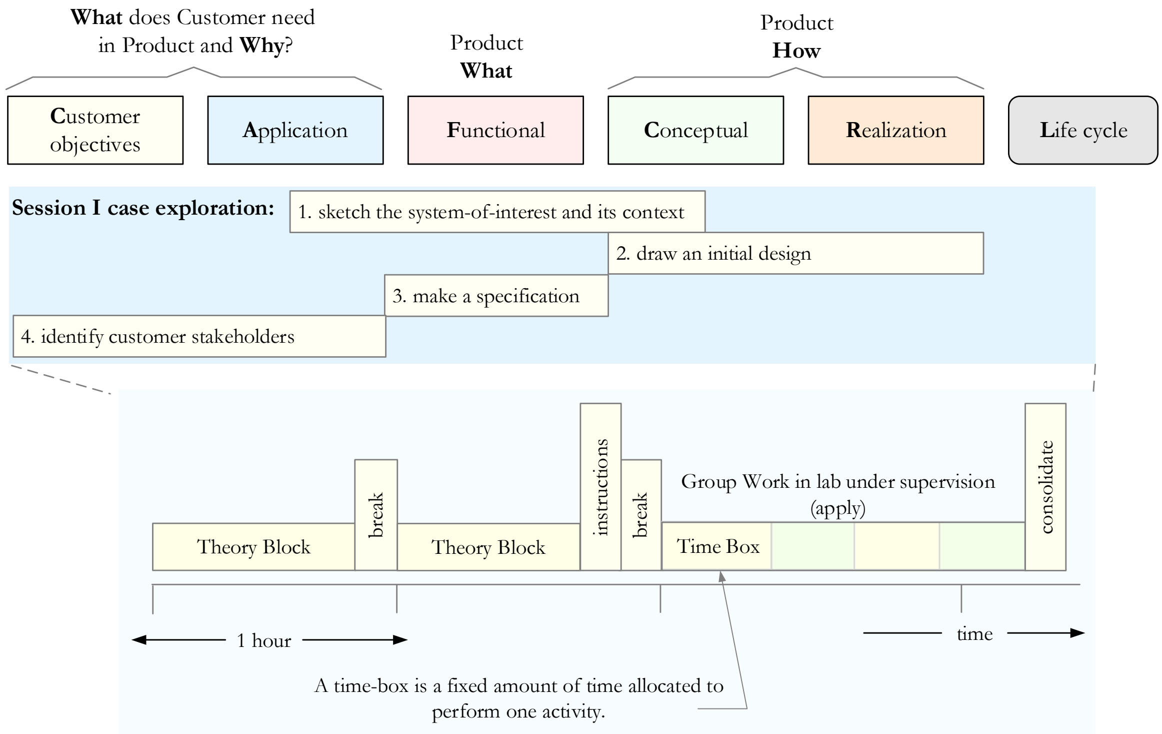

Figure 1 The activities of one session, "case elaboration," within the CAFCR framework. The first session is an example out of four sessions illustrated for simplicity and space limitations, adapted from (Muller and Bonnema, 2013).

Figure 2 A team engaged in the CAFCR lab activities. In 2025, the case involves designing an innovative system to assist elderly people in managing their daily activities.

The assessment of the course effectiveness. As part of the course, students submit a short individual reflection report to highlight their main learning points. Additionally, they complete a formal course evaluation form provided by the department. The authors also plan to conduct a survey at the end of the spring 2025 semester to gather student feedback on their experience in an interdisciplinary team environment. As a first step, the authors have started analyzing reflection reports from the past six years to evaluate the course's effectiveness in fostering interdisciplinary skills and mindsets. Although this analysis is ongoing, initial findings reveal that students value the opportunity to work in interdisciplinary teams. They primarily emphasize interdisciplinary skills and mindsets, including effective communication, shared understanding, addressing challenges in group dynamics, collaborating with other engineering disciplines, and solving problems from multiple perspectives. Additionally, feedback suggests that students have successfully grasped key concepts and techniques introduced in the course, including visualization, timeboxing, quantification, and iteration.

Discussion

This paper proposes a course on the fundamentals of SE to enhance and facilitate interdisciplinary skills and mindsets among undergraduate engineering students. Initial findings from student feedback indicate that "interdisciplinary team" is the most frequently mentioned learning point in the reflection reports. This term includes two key elements: interdisciplinary and team. For the interdisciplinary aspect, students frequently report terms such as visualization, timeboxing, quantification, and iteration. Regarding teams, students emphasize the importance of cooperation, effective communication, and managing team dynamics.

These results suggest that introducing SE fundamentals and concepts to undergraduate students can help the development of interdisciplinary team skills and mindsets. Visualization helps students communicate and share understanding with team members across various engineering disciplines. Iterations enhance understanding over time, enabling students to accumulate knowledge and deepen their understanding. Quantification enables students to be more specific and concrete, providing early indications of critical aspects that require the team's attention. Additionally, timeboxing helps students manage team activities effectively within designated time constraints and encourages them to achieve satisfactory results within the allocated time. Our findings align with previous research that emphasizes the importance of introducing interdisciplinary skills in engineering education (Lattuca et al., 2017; Ghannam & Chan, 2023). Similar to approaches adopted by Li et al. (2015), our course combines PrBL, TBL, and PBL, which enhance students' interdisciplinary competencies.

The broader structure of WIL at USN also supports these outcomes. The course stimulates real-world engineering problems and is part of a structure that includes structured industry placements in the undergraduate engineering program, employer partnerships, and a reflective course in the master’s program in SE. This approach links course-level activities at the micro level with program-wide WIL practices at the macro level. Through an industry reference group, we receive ongoing input on curriculum alignment with evolving industrial needs that affect both bachelor's and master's courses in engineering, particularly within SE. This bidirectional exchange ensures that students experience a curriculum grounded in theory and responsive to practice.

At the doctoral level, USN, Kongsberg offers a PhD program emphasizing the “industry-as-laboratory” research methodology (Ali et al., 2022; Potts, 1993), where candidates work closely with industry partners to conduct applied research. This is further supported by an industry research school that provides funding and facilitates internships within industry for PhD candidates. These initiatives reinforce a vertically integrated WIL structure that extends from undergraduate to doctoral education (“Industrial Research School in Complex Systems,” 2022).

Muller (2015) recommends utilizing these four interdisciplinary terms—visualization, timeboxing, quantification, and iteration—to establish a shared understanding and effective communication among various stakeholders. By incorporating these principles, our course aims to prepare students to work effectively in interdisciplinary team settings and meet the industry's demands and expectations.

The results are promising; however, there are some limitations. The findings are based on implementing courses within the Norwegian context, particularly at USN, Campus Kongsberg, where strong industry collaboration and national curricula support this model. As such, the generalizability to other institutional or cultural contexts may be constrained. Additionally, while the CAFCR+ framework has proven effective in our environment, institutions without knowledge about SE fundamentals may face challenges in adopting it without adaptation, especially since Muller, a co-author of this paper, developed the CAFCR+ framework (Muller, 2004).

Conclusion

The undergraduate engineering curriculum should incorporate an interdisciplinary mindset to prepare students for the demands of industry. This paper proposes introducing a course on SE fundamentals to expose engineering students to interdisciplinary teamwork. The course combines theory with hands-on lab activities, utilizing the CAFCR+ framework. Students are introduced to various SE tools and methodologies, including the traditional V-model and key techniques such as visualization, timeboxing, and iteration.

Initial findings from student reflection reports, though still in progress, indicate that students value the opportunity to work in an interdisciplinary team. Furthermore, their feedback reveals that they have grasped elements such as visualization, timeboxing, quantification, and iteration, particularly in the interdisciplinary aspect, on the one hand. On the other hand, they grasped elements such as cooperation, effective communication, and managing team dynamics, which are essential for the team aspect.

Future work will explore how this course model can be adapted and scaled. Currently, the course is offered at the Campus Kongsberg undergraduate engineering program, and there are ongoing discussions to extend it to other campuses within USN that offer engineering education. As part of this scaling effort, instructors also consider strengthening feedback loops by involving industry stakeholders more directly in course design and curriculum updates. While we already include an external assessor from industry in evaluating individual and group-based lab activities, future efforts may expand this role to include formative feedback or mentoring during the course. Finally, we plan to analyse student reflection reports more systematically across a larger dataset to better understand the longitudinal impact on interdisciplinary competence development. These efforts also align with a broader institutional commitment to WIL across all levels of engineering education, including existing initiatives at the PhD level that incorporate internships and industry collaboration through the “industry-as-laboratory” model and the industry research school.

References

Ali, H.B., 2021. Unlocking the power of big data within the early design phase of the new product development process: A case study in a Company, in: INCOSE International Symposium. Wiley Online Library.

Ali, H.B., Langen, T., Falk, K., 2022. Research methodology for industry-academic collaboration – a case study, in: INCOSE International Symposium. pp. 187–201. https://doi.org/10.1002/iis2.12908

Brezing, A.N., Löwer, M., 2008. Engineering and industrial design: an integrated interdisciplinary design theory, in: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. pp. 351–357.

Chettiparamb, A., 2007. Interdisciplinarity: a literature review. Southampt. Univ. Southampt.

Criteria for Accrediting Engineering Programs, 2025 - 2026 - ABET [WWW Document], 2025. URL https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2025-2026/ (accessed 3.11.25).

Fleming, J., Ferns, S.J., Zegwaard, K.E., 2023. Benefits of work-integrated learning for host organizations, in: The Routledge International Handbook of Work-Integrated Learning. Routledge, pp. 113–130.

Ghannam, R., Chan, C., 2023. Teaching undergraduate students to think like real-world systems engineers: A technology-based hybrid learning approach. Syst. Eng. 26, 728–741. https://doi.org/10.1002/sys.21683

INCOSE, Wiley, 2015. INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities. John Wiley & Sons, Incorporated, New York.

Industrial Research School in Complex Systems [WWW Document], 2022. URL https://inrescos.usn.no/ (accessed 6.18.25).

Lattuca, L.R., Knight, D.B., Ro, H.K., Novoselich, B.J., 2017. Supporting the Development of Engineers' Interdisciplinary Competence: Supporting Engineers' Interdisciplinary Competence. J. Eng. Educ. 106, 71–97. https://doi.org/10.1002/jee.20155

Li, T., Raghunath, N., Hölttä-Otto, K., Arpak, A., Nanayakkara, S., Telenko, C., 2015. Teaching interdisciplinary design between architecture and engineering: finding common ground while retaining disciplinary expertise, in: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V003T04A010.

Muller, G., 2024. Bachelor Course Systems Engineering: Architectural Reasoning; Homework.

Muller, G., 2004. CAFCR: A multi-view method for embedded systems architecting. balancing genericity and specificity.

Muller, G., Bonnema, G.M., 2013. Teaching Systems Engineering to Undergraduates; Experiences and Considerations. INCOSE Int. Symp. 23, 98–111. https://doi.org/10.1002/j.2334-5837.2013.tb03006.x

Nair, C., Patil, A., 2008. Industry vs universities: re-engineering graduate skills-a case study.

Nasjonalt råd for teknologisk utdanning (NRT), 2011. Nasjonale retningslinjer for ingeniørutdanning.

Pazos, P., Cima, F., Kidd, J., Ringleb, S., Ayala, O., Gutierrez, K., Kaipa, K., 2020. Enhancing teamwork skills through an engineering service-learning collaboration, in: 2020 ASEE Virtual Annual Conference Content Access, Virtual Online.

Potts, C., 1993. Software-engineering research revisited. IEEE Softw. 10, 19–28.

Wisniewski, E.C., 2018. Novice engineers and project management communication in the workplace. Tech. Commun. 65, 153–168.