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Integrating Challenge-Based Learning in a Vertical Classroom: A Cross-Disciplinary Approach to Teaching Microfluidics for Biomedical Engineering and Mechanical Engineering Students

Burcu Gumuscu [1] [a,b], Lanhui Li [a,b,e], Kalpit J. Bakal [b,c], Oscar M.J.A. Stassen [b,c], Hans M. Wyss [b,c], Jasmina Lazendic-Galloway [d]

[a] Biosensors and Devices Lab, Biomedical Engineering Department, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands

[b] Institute for Complex Molecular Systems, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands

[c] Department of Mechanical Engineering, Microsystems, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands

[d] innovation Space, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands

[e] Base of Red Bird MPhil, College of Future Technology, Hong Kong University of Science and Technology (Guangzhou), Guangzhou, LG5313, China.

ABSTRACT

The paper presents a case study illustrating the implementation of a combined master's level and third-year bachelor's Lab-on-a-Chip Microdevices course using a Challenge-Based Learning (CBL) approach. We describe the course's design, the implementation, and the observed impact of adopting this innovative approach in the form of action research. We use a survey and a focus group discussion to investigate students' perceptions of learning through the CBL approach. The gathered insights highlight the appreciation for practical application and industry collaboration in the course. Some issues related to class preparation and clarity of guidelines for working on challenges have also been identified, and a re-design addressing these issues was co-created between the instructors and students during the focus group session. Our study offers a blueprint for designing hands-on experiment-oriented courses in collaboration with industry and highlights the potential of CBL to enhance technical proficiency and foster innovation in interdisciplinary engineering education.

KEYWORDS

Challenge-based learning,
Active learning,
Science education,
Vertical classroom,
Microfluidics,
Biomedical engineering education,
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[1] Corresponding Author : Burcu Gumuscu – b.gumuscu@tue.nl, Biosensors and Devices Lab, Biomedical Engineering Department, Eindhoven University of Technology, Eindhoven, 5600 MB, Netherlands

Introduction

In recent years, engineering education has increasingly embraced innovative pedagogical approaches to better prepare students for the complexities of modern engineering challenges. Traditional lecture-based methods, while foundational, often fail to fully engage students or develop essential skills such as critical thinking, problem-solving, and collaborative work (e.g., Montesinos, Salinas-Navarro, and Santos-Diaz 2023; Haenen, Vink, Sjoer, and Admiraal 2024).

The teaching environment for Microfluidics education, including bachelor's and master's levels, has often been characterized by conventional methods with limited emphasis on autonomous and reflective thinking (e.g., Bezrukov and Sultanova 2021). The prevailing culture in this setting tends to be protocol-driven, hindering functional autonomy and not supporting the development of skills crucial for continuous learning and innovation (Harris, Bransford, and Brophy 2002; Singh, Ferry, and Mills 2018). Introducing reflective thinking can enable students to move beyond conventional practices and foster autonomy by emphasizing best practices that enhance experimental and design performance (Boud 2016; Lazendic-Galloway et al. 2020).

In the domain of microfluidics education, the current focus often revolves around technical knowledge and experimental skills. However, there is a recognized need to integrate learning approaches that emphasize not only technical proficiency but also reflective practice and transformative learning, such as Challenge-Based Learning (CBL) (Gallagher and Savage 2020; Lazendic-Galloway et al. 2021; Coulson and Harvey 2013). This shift aligns with the dynamic landscape of modern biomedical engineering and mechanical engineering training, on which basis our course “Lab-on-a-Chip Microdevices” has been built as an integral component of both disciplines.

Traditional biomedical engineering education, with its emphasis on cell and tissue biology and mechanics, falls short in addressing the contemporary demand for expertise in building functional microdevices to tackle biomedical engineering challenges (e.g., Wikswo et al. 2013; Low et al. 2020). On the other hand, mechanical engineering education may oversee the fundamental concepts that are necessary for biomedical applications whereas mechanical engineers are also often asked for building tools or technology. These emerging professional demands reveal an education gap, especially in reflective design processes requiring complex multidisciplinary expertise. Therefore, we (the first five authors) were motivated to bridge this gap by designing a hands-on course that integrates technical proficiency with reflective practice, fostering autonomy and innovation in microfluidics education. The approach presented here is in the form of action research and a case study and should be suitable for a broad range of educational settings. In this paper, we present our teaching and research design, including the data collection and analysis. Finally, we evaluate the findings in terms of students' learning experience and teachers’ reflection and conclude with the insights gathered for further improvement of the course.

Literature Review

The educational framework we used to design the new course in Microfluidics integrates constructivism, learner-centered teaching, and situated learning, which have been combined within the CBL set-up of the course. CBL immerses students in real-world problems, promoting active engagement and practical skill development that mirrors professional engineering practice. CBL is increasingly recognized as a transformative approach in higher education (Gallagher and Savage 2020; Perna, Recke, and Nichols 2023), and engineering in particular (Kohn Rådberg et al. 2020). This pedagogical method aligns with the needs of modern engineering education by emphasizing problem-solving and interdisciplinary collaboration, immersing students in authentic challenges that require active engagement, fostering both technical and transversal skills essential for the evolving engineering landscape, such as teamwork, communication, and adaptability (Kohn Rådberg et al. 2020). Engineering problems often span multiple disciplines. CBL facilitates interdisciplinary learning by encouraging students to work in diverse teams, drawing on different areas of expertise to solve complex challenges (Membrillo-Hernández et al., 2021). By working on real-world challenges, students develop robust problem-solving frameworks that they can transfer to various engineering contexts. This experiential learning process builds confidence and equips students with practical skills that are highly valued in the workforce (Clegg & Diller 2018).

Constructivist learning encourages learners to integrate past experiences with current knowledge, facilitating active questioning, analysis, and the construction of their understanding (Yuen and Hau 2006). Social constructivism, involving collaborative learning with shared goals, provides students with the opportunity to discuss, explain, and defend ideas, promoting reflection and a deeper understanding of the subject matter (Schreiber and Valle 2013). Learner-centered teaching, such as CBL, shifts the focus from mere knowledge acquisition to developing students' competence, aligning with the contemporary emphasis on lifelong learning and increased student responsibility (Gallagher and Savage 2020; Membrillo-Hernández et al. 2021). Situated learning, which underscores the social and cultural aspects of learning, connects education to authentic and meaningful experiences by simulating professional workplace settings (McLellan 1996).

To create a blended learning environment for our CBL course and enable us to guide students through a structured learning experience, we used Salmon's five-stage model of teaching and learning online that emphasizes access, motivation, socialization, information exchange, active learning, and development (Salmon 2012). By adapting this model to the context of our course, we aim to create a learning environment that is both structured and adaptable, fostering reflective practice and transformative learning in the field of Microfluidics. When designing the Lab-on-a-Chip Microdevices course, integrated into the curriculum of the Biomedical and Mechanical Engineering departments at our university, we aimed to align innovative teaching methodologies with current technological trends and provide students with the necessary skills for navigating the evolving landscape of modern biomedical and mechanical engineering (Andersson and Van Den Berg 2004; Choi et al. 2007; Khademhosseini and Langer 2016).

Course design

Context

The Lab-on-a-Chip Microdevices (LOCM) course is an interdisciplinary course hosted by two departments at the Eindhoven University of Technology. It is given to final-year bachelor-level biomedical engineering students and first-year master-level mechanical engineering students. LOCM is therefore used as a component for both engineering minor and major. It is offered in the third quarter of the academic year, which is just before the graduation project, as a complementary unit for a hands-on and active learning experience. For the master students, LOCM is a successor of a microfabrication course in the curriculum, with the aim to teach students the techniques and applications of the microfluidics field. Through LOCM, our goal is to guide students through a comprehensive learning journey into the domain of professional-level microfluidic engineering, and by mixing bachelor- and master-level students, to foster peer learning across different disciplines. This approach involves a blend of theoretical foundations delivered through lectures, complemented by team-based and individual self-study sessions utilizing CBL methodologies. Curated by industry partners, real-life challenges further enrich the learning experience, bridging the gap between theoretical knowledge and practical applications.

The majority of the ~30 students enrolled in LOCM are science and engineering students from diverse departments, including biomedical engineering (~30%), mechanical engineering (~64%), applied physics (~3%), and chemistry & chemical engineering departments (~3%). Attendance at all sessions is mandatory, and all students generally meet that criterion.

Implementation of challenge-based learning

The LOCM course started in 2022 and represents an evolved iteration of the Microfluidics-put-to-work (MPW) course, offered by the Mechanical Engineering department to master's students over seven years. The MPW curriculum primarily followed a traditional teaching approach, featuring a 4-hour long block of theory-based lectures where students engaged with the teaching staff. To ensure optimal attention and support for all students, the course capacity was limited to 40 students annually. Additionally, students participated in hands-on laboratory sessions, undertaking a predetermined project and analyzing experimental observations within a specified framework. The laboratory sessions were run with up to 25 students, organized into teams of 5 for collaborative work on the project, and led by a teaching assistant (TA). Students were presented with two fixed laboratory projects directly aligned with the lecture content. Both theory and laboratory components maintained identical pacing throughout the quarter, a period typically spanning 10 weeks, including two weeks dedicated solely to examinations.

In 2021, the responsible lecturer (the first author) initiated a reconstruction of the MPW course with funding from the Eindhoven University of Technology Education Innovation program. This program, aimed at improving education quality through an emphasis on CBL, aligns with the university's 2030 goals to cultivate "independent engineers of the future." In pursuit of this overarching objective, we embarked on a significant transformation of the existing course, leading to the establishment of the LOCM course.

We designed LOCM strategically to incorporate an open-ended, CBL approach into a laboratory environment, fostering an interdisciplinary setting for students with diverse knowledge levels. Taking into account limitations of lab equipment usage and material availability, we decided that the focus of deliverables for the projects should be on identifying viable solutions and establishing guidelines. These efforts, therefore, aimed to integrate open-ended project structures without placing undue burdens on laboratory resources, ensuring the effective implementation of innovative teaching methodologies.

To achieve this, we invited industrial partners to become "Challenge Owners" for the CBL projects. The concept involves companies providing recent and valid project proposals based on ongoing research within their R&D departments. If necessary, the company supplies students with equipment and reagents, such as their products (materials, chips, etc.). Additionally, tools and standard chemistry laboratory equipment are readily accessible to students at the university. The company is not required to disclose information related to the IP rights of the business but is expected to offer consultancy to students for efficient project execution. Each CBL project lab session is supervised by a dedicated TA per student team. The support for laboratory sessions has expanded to involve two departments, allowing us to accommodate up to 50 students, with the potential for further extension. This enhancement in capacity facilitated a more interdisciplinary learning environment, promoting collaborative engagement and exploring diverse perspectives.

As a complementary layer to the work on the main challenges through the CBL project, we provide online lectures that cover theory and weekly mini-challenges for students to practice problem-solving. These mini-challenges are discussed within the classroom with responsible teachers every week. The theory and lab sessions operate at their own pace (in terms of the content), but they are intricately linked, creating a cohesive and comprehensive learning experience.

Thus, LOCM fosters increased student engagement by creating a real-life, hands-on learning experience. With 30 and 28 students enrolled in the first two years, respectively, the course achieved better alignment between lectures and labs. The lead author, also the responsible teacher, was present during all lab and theory sessions, facilitating enhanced interaction. Practical activities in the lab sessions were updated from more theory-related tasks to real-life, hands-on tasks using case studies by industry partners.

Classroom activities and assessment

The classroom activities are divided into three categories in LOCM. On the first day of the course, the students are put into teams of up to 5 members. Each team consists of at least one member from a bachelor’s, master's, mechanical engineering, and biomedical engineering program. Each team chose one of the challenges offered by at least two different industry Challenge Owners. They remain in these teams during both theoretical and laboratory sessions to promote cooperative learning.

Theory sessions: The theory sessions were structured around the five main domains in microfluidics: microfabrication, liquid transport and handling, cells on chip, sensing and separation, and droplet microfluidics. In the initial course pilot, we provided students also with weekly mini-challenges, which were presented after a lecture. Each mini-challenge was tailored to specific learning objectives within each domain and sufficiently open for students to come up with their own ideas about what the solution could be. Mini-challenge descriptions included key terms and references from published literature. To stimulate classroom discussions and peer-to-peer learning, students were required to prepare their solutions to mini-challenges via presentation the following week. Facilitated by the responsible teachers and TAs, these discussions delved into the ideas presented by the students and offered an expert’s approach to the problem, with an intent to close the gap between theory and application and teach students gradually how to tackle the main CBL challenge (the lab project).

Following the pilot edition in 2022, in the 2023 edition of the course, we recorded the lectures and made them available for online access before classroom sessions. In this way, we wanted to free more time in class for teachers and TAs to listen to team solutions of the mini-challenges, offering feedback and presenting reference solutions. The remaining time was dedicated to introducing the next week's mini-challenge before students moved to their group rooms for guided self-study sessions to address the new mini-challenge. During the guided self-study, TAs and responsible teachers visited groups for on-demand consultations. This cycle was applied consistently until the end of the course. For mini-challenges with a heavier workload, we allocated two weeks instead of one for student completion.

Laboratory sessions: The work on the main CBL challenge in the laboratory sessions involved the complete experiment design circle, encompassing design, build, and measure phases (Figure 1). In this manner, students learned commonly used prototyping techniques, conducted measurements, and interpreted data, thereby experiencing the entire cycle of conducting experiments. The labs were intended for students to activate their preexisting knowledge in engineering design, statistics, and computational programming (e.g., simulations and calculations). Students were also expected to possess basic chemical and biological lab skills such as pipetting and microscopy. The weekly laboratory sessions were held on one day of the week, corresponding to 50% of the course time during contact hours, excluding self-study time.

To tackle the main CBL project and conduct the laboratory sessions, student teams first had to formulate a project plan during the initial two weeks. Subsequently, starting from the third week, their focus shifted towards crafting a design (or utilizing an existing one, as standard templates were applicable to address various lab-on-a-chip issues), simulating the design for fluid mechanics characterization, fabricating the design, and performing measurements as specified by the industry Challenge Owners.

For the work on the main CBL project, students were tasked with exploring the fundamental challenges in the aforementioned topics aligned with their projects. They initially deliver a written project plan, and as a final output, they submit a written design, simulation, and prototyping report, and an oral final presentation covering all the project steps.

Figure 1. *The steps for the project work (the main challenge) in the Lab on a Chip Microdevices course. Students will work on the projects in teams of five to perform these steps. Build and measure phases require lab use. While working on the project, every week, the students will solve the challenges introduced in challenge-based learning sessions, which will involve topics regarding (but not limited to) fluid mechanics, mass transport, prototyping, optical & biochemical measurement, and/or cell handling methods.*

Pre-class activities: The weekly mini-challenges were structured as modules, restricting access to the next module until the current one was completed. Before face-to-face sessions, students prepared by reviewing specific textbook sections and watching up to 60-minute voice-over slide presentations. Subsequently, they completed a non-graded, formative quiz targeting key learning objectives, aiming for at least 85% correct answers. The students also crafted a quiz question themselves, which they then answered, and TAs reviewed those answers to check students' comprehension of the material. These activities, including the qui formulation task, facilitated just-in-time teaching, addressing the issues related to conceptual understanding. The students received automated feedback through the quiz grade, which indicated the overall grade but not the correctness of the questions. This modular format of content delivery allowed for enriching instructional material with current research. Before laboratory sessions, students were required to complete a task just in the first week when they needed to form teams based on project interests and read project proposals in preparation for the lecture (Table 1). A summary of associated assessments can be found in Table 2.

Table 1 : *The overall course structure.*

		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Pre-class activities	**Activity**	Watch pre-recorded theory lectures							-
	Assessment	Compulsory but not-graded quiz Prepare your own quiz question							-
Session1 (4h) **Hands on learning through the main CBL project**	**Activity**	Hands-on work on projects in the lab (4h) with TA support							
	Assessment	→ Prepare project proposal			→ Conduct experiments				
Session 2 (4h) Theory & mini-challenges	**Theory**	Live lecture and Q&A (1h)			Live lecture and Q&A (1h)				-
	Assessment	n/a	mini-CBL challenge 1 presentation	mini-CBL challenge 2 presentation		mini-CBL challenge 3 presentation	mini-CBL challenge 4 presentation		Summative exam (written and oral)
	Self-study (TA supported)	New challenge introduction and group work	New challenge introduction and group work	New challenge introduction and group work		New challenge introduction and group work	New challenge introduction and group work		Group work

Table 2: *Summary of the assessments in the course.*

Assessment	Contribution to the final grade (%)
Homework (pre-class activity)	Compulsory
Assignment 1 (mini challenge)	10
Assignment 2 (main proposal)	20
Assignment 3 (oral presentation of main challenge)	30
Written exam	40
Total	**100**

In-class activities (theory sessions)

The theory sessions, in general, started with the students' group presentations on their mini-challenges. This practice served as a formative assessment with a small contribution to the final grade (10%). The entire class first listened and commented on each group's solution to the mini-challenge of the week; then the teachers presented their ideas to give the students an idea of how an expert would have approached the challenge. Following this conclusion of the previous mini-challenge, the students were then presented with a new mini-challenge and started working on it for the rest of the day. This time of independent work comprises the self-study component of the course. Both the teachers and TAs supported students in their self-study through face-to-face interactions and encouraged them to ask questions while working on their weekly mini-challenges. The students usually also met one or two times per week to work on their mini-challenges, as well as the main CBL challenge, and the TAs were open to answer their questions during designated consultation times during the regular sessions.

Our teaching team's motto is "answer a question with another question" (also known as Socratic questioning). With this approach, we aim to encourage students to develop critical thinking and become self-sufficient. Therefore, if a student was still struggling, we offered sufficient help to get them over what they stumbled on. The responsible teachers and TAs met bi-weekly to discuss and evaluate the progress of each group, ensuring efficient monitoring of their overall progress.

Lab sessions (practical work)

During the laboratory sessions, one TA was always present in the laboratory to help with technical issues, while each group received a minimum of 30 minutes of interaction time with the group's TA. The laboratory sessions were always set to start with a 5-minute Scrum meeting, which has two aims: (1) answer any possible questions related to equipment and lab use, (2) prevent any accidents, and monitor the safe use of the laboratory.

We train students to use microfabrication, focusing on soft lithography due to the straightforward nature of the technique. The students then use these chips that they create during the training session, which increases their self-confidence and learning motivation. We also offer extra hands-on, non-assessed training to the master students related to the production of glass capillary making.

Mentoring by challenge owners

The industry Challenge Owners meet students in class four times per quarter: the first week (when the students start building the project proposal), the third week (when written feedback is provided on the project proposal), the fifth week (when students start the experiments and gained some experience with operating tools and equipment for the project work), and the eighth week (the final presentation of the project work). The students also self-initiate meetings with their Challenge Owners throughout the quartile on a need basis.

At the end of the quarter, the student teams delivered a 10-minute presentation with a 5-minute Q&A session, summarizing their progress and conclusions about the project work. This served as a summative assessment (30% of the total grade). The students received verbal feedback from the teachers and industry partners, as well as their project grades. We also provide students an opportunity to self-reflect on their teamwork via a peer-review form. They grade the work performance of each member out of 10 and give a reason why this grade would be appropriate. This enables an individual adjustment of the final presentation grade as follows: +1: if one gets an average of 9 or 10; 0: if one gets an average of 7 or 8; -1: if one gets an average of 4, 5, or 6; -2: if one gets an average 2 or 3; -3: if one gets an average 1. Our aim with this approach is to stimulate balanced work. The students do not have access to the comments but only to the peer-review grade. Particularly, the individual grade adjustment recognizes extreme contributors or free-riders while it has more neutral consequences for balanced contributors, which has been appreciated by the students.

By the end of the quarter, the students who completed all online modules also book a spot for a final, summative exam that carries 40% of the total grade. This exam is in the form of an oral exam for master students and a written exam for bachelor students. In this way, we can assess the knowledge and skills for each level appropriately. The topics cover only the theory content. The duration of the oral exam is 60 minutes and is run by a responsible teacher and a TA. Later on, all teachers listen to the recording of the session to get an agreement on the final grade. The written exam consisted of 10 questions, where 5 exam questions were multiple-choice, and 5 exam questions were open-ended. The duration of the exam is set to 60 min.

Constructive alignment

Our design of learning objectives has been carefully matched with learning activities and assessment through constructive alignment (Biggs 1996).

Mini-challenges (10% of the grade): These mini-challenges are directly linked to the weekly lectures and encourage students to engage in problem-solving, critical thinking, and applying theoretical concepts to practical scenarios. They are presented the following week for discussion, peer-to-peer learning and active participation are fostered, requiring students to evaluate and create their solutions, which aligns with the higher levels of Bloom's taxonomy (Anderson and Krathwohl 2001).

The main challenge and oral presentation (50% combined): The lab CBL project is the culmination of their learning, focusing on interdisciplinary collaboration and real-world applications. This project is open-ended, which aligns well with authentic, student-driven learning. The oral presentation component emphasizes communication skills, another key objective in interdisciplinary work, and which also addresses higher-order cognitive skills (analyzing, evaluating, creating).

Exam (40% of the grade): While CBL emphasizes hands-on learning, the exam serves to ensure that students have also achieved the foundational knowledge needed in the field. Given that microfluidics involves complex theoretical principles, the exam aims to assess the understanding of core concepts and problem-solving skills in a structured manner, ensuring that students not only engage in practical challenges but also retain and understand the underlying scientific principles.

Research design

This study employs action research as the research methodology to further enhance and refine the teaching framework. Action research is a systematic process of reflection, inquiry, and action undertaken by individuals regarding their professional practice (e.g., Kember and Gow 1992). By integrating action and critical reflection, action research bridges the gap between theory and practice, progressively accumulating practical knowledge to enhance overall practice (Gibbs et al. 2017). In the context of this study, the cyclical nature of action research provided an optimal mechanism for designing, implementing, evaluating, reflecting on, and modifying the educational framework guiding the creation of this multidiscipline-compatible, vertical classroom module for microfluidics education. This dynamic approach aligns seamlessly with the evolving landscape of microfluidics education, fostering an environment where theory and practice harmoniously coexist to benefit student learning and development in multiple layers.

In addition to conducting action research, which captures the instructor's reflective practice cycle, this study employs empirical research methods to gather comprehensive data from the learners. A mixed-method approach is used, comprising both quantitative and qualitative data collection techniques, carried out by a discipline-based educational researcher unrelated to the course (the sixth author) in order to ensure objectivity.

The project has been approved by TU/e Ethics Review Board no. ERB2021ESOE18.

This study can also be classified as a case study (Case and Light 2011) because it focuses on an in-depth exploration of a particular educational setting within its real-world context. By examining this specific instance, the study provides insights that can inform broader educational practices. The case study approach allows for a detailed examination of the course design, implementation, and outcomes, making it possible to generate findings that are transferable, fully or partially, to similar educational settings and disciplines.

Data Collection

In the last week of the course, an anonymous survey was conducted for quantitative data collection, aimed at evaluating the effectiveness of the CBL approach and overall student satisfaction. The survey included a combination of eight multiple-choice questions with Likert 5-point scale questions and three open-ended responses.

Table 3. *The survey questions used in this case study.*

Survey questions	The scale
Q1. How effective are the online recorded lectures in helping you understand the course concepts? Q2. How well do you think the hands-on lab project enables you to apply theoretical knowledge to real-world applications? Q3. How effectively do you feel the course facilitates collaboration between students and industry partners through the main challenge (the case)? Q7. Considering the workload and the learning value, rate how well-balanced you find the distribution of efforts across different course components (lectures, labs, projects):	Not at all – Great deal
Q4. The weekly challenges help me apply theoretical concepts in practical scenarios. Q5. The interdisciplinary classroom has enhanced my problem-solving skills by exposing me to varied approaches and methodologies. Q6. The feedback and standard solutions provided after the weekly mini-challenges deepened my understanding of the subject matter. Q8. The total workload for this course is appropriate for the credit value.	Strongly Disagree – Strongly Agree
Q9. Which aspect of the course do you find most effective at this moment? Q10. Which aspect of the course do you find most challenging at the moment, and how do you think it could be improved? Q11. Any other things you would like to share?	Open-ended

At the end of the course, a focus group was conducted with three students, who were asked to be group representatives of the three student teams (related to the industry CBL projects). Two responsible lecturers and two TAs were also present and this session was designed to elicit a “360 degree” feedback on the course structure, content, and delivery, as well as any issues with the industry projects. The questions were semi-structured (see Table 4), allowing for guided questions yet providing flexibility for participants to raise additional points, and designed to probe areas of strength and opportunities for improvement from the perspectives of both students and lecturers. Despite the presence of lecturers, efforts were made to ensure a safe environment where students felt comfortable expressing honest opinions. This collaborative co-creation process between instructors and students during the session facilitated meaningful suggestions for revisions of the course structure and ensured that the redesigned course better aligned with students' learning needs.

Table 4. *The semi-structured focus group questions used in this case study.*

Focus group questions
Q1. Where do you think balance can be improved between different components of the course (lectures, labs, projects, self-directed work) to address your main learning objectives?
Q2. Do you feel the learning from the smaller weekly/biweekly CBL was effective?
Q3. Do you feel that the CBL project facilitates effective learning, or does it need improved structure or support (from both lecturers and challenge owners)?

Data Analysis

The surveys included both Likert-scale and open-ended questions designed to capture students' attitudes toward various aspects of the course, such as engagement, content relevance, instructional quality, and perceived learning outcomes. These quantitative responses were analyzed using descriptive statistics (frequencies and percentages) to identify patterns and trends in student satisfaction and engagement, as well as any areas of concern.

The survey also included open-ended questions to gather qualitative insights into students' personal experiences and suggestions for course improvement. Responses from these open-ended questions were analyzed through a process of thematic coding. The initial step involved reading through all responses to familiarize the researchers with the data. Next, the data were systematically coded to identify key phrases or concepts. These codes were then organized into broader themes that reflected students' opinions about specific elements of the course, such as the structure of assessments, the clarity of instructional materials, and the overall learning environment. Where relevant, cross-tabulation was used to explore relationships between different survey items and these themes (see Table 4).

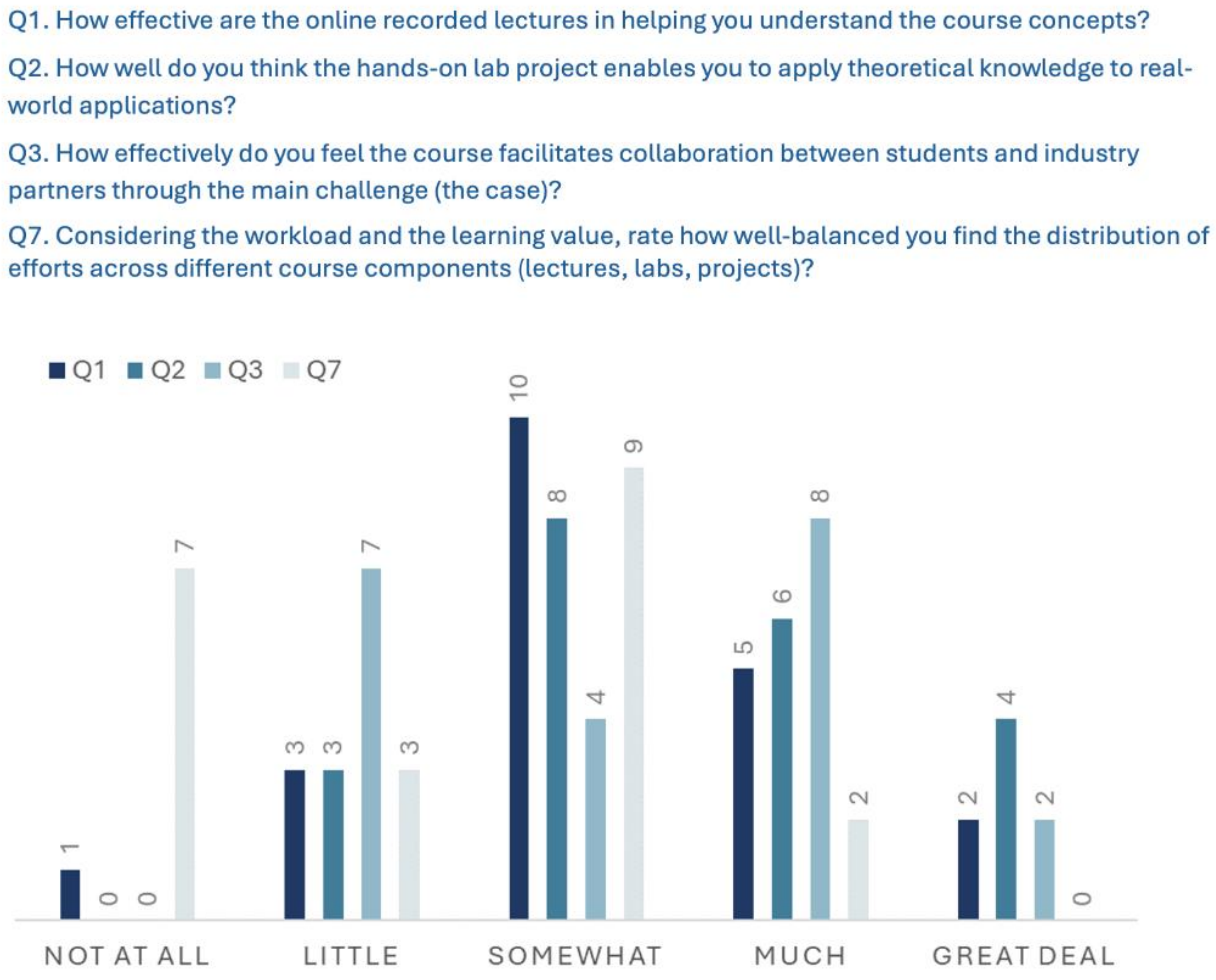
In addition to the survey, a focus group discussion was conducted to gather more in-depth qualitative data. The discussions were audio-recorded and transcribed verbatim. This transcript was then analyzed using thematic analysis following the steps outlined by Braun and Clarke (2006). An initial set of codes was generated based on recurring comments after a thorough reading of the transcript and were subsequently grouped into themes that captured significant patterns in the data. The themes were refined through an iterative process, ensuring they accurately reflected the core messages conveyed by the participants.

Throughout the qualitative analysis of both open-ended survey questions and the focus group discussions, particular attention was given to both positive and negative student feedback to identify specific areas where the course was excelling and where improvements could be made. Overall, the mixed-methods approach ensures robust analysis and triangulation of data to validate findings and enhance the overall reliability and depth of the study.

Results

Insights from the survey

The student response data provides insights into various aspects of the course, including the effectiveness of online lectures, hands-on labs, collaboration, workload balance, and more. The responses to eight multiple-choice questions from 21 students are presented as frequency plots in Figures 2 and 3. The themes identified from open-ended questions are presented in Table 5. Combining the insight from these results, we discuss the key findings about student perceptions and experiences.



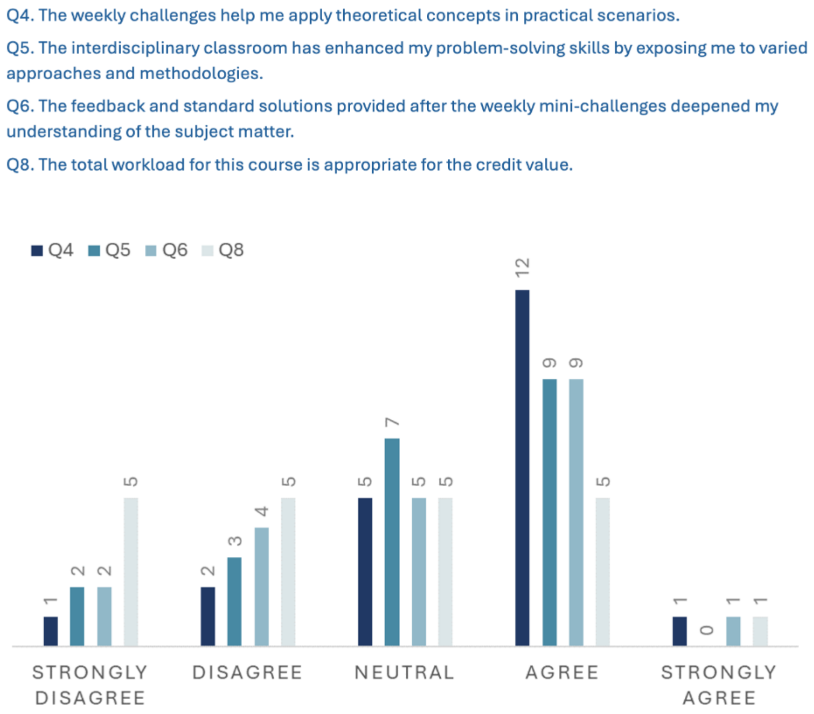
Q1. How effective are the online recorded lectures in helping you understand the course concepts?

Q2. How well do you think the hands-on lab project enables you to apply theoretical knowledge to real-world applications?

Q3. How effectively do you feel the course facilitates collaboration between students and industry partners through the main challenge (the case)?

Q7. Considering the workload and the learning value, rate how well-balanced you find the distribution of efforts across different course components (lectures, labs, projects)?

Figure 2. *The survey responses to Q1, Q2, Q3 and Q7 are given as an absolute frequency of students' agreeing or disagreeing with a statement (N=21).*



Q4. The weekly challenges help me apply theoretical concepts in practical scenarios.

Q5. The interdisciplinary classroom has enhanced my problem-solving skills by exposing me to varied approaches and methodologies.

Q6. The feedback and standard solutions provided after the weekly mini-challenges deepened my understanding of the subject matter.

Q8. The total workload for this course is appropriate for the credit value.

Figure 3. *The survey responses to Q4, Q5, Q6, and Q8 are given as an absolute frequency of students' agreeing or disagreeing with a statement (N=21).*

Table 5. *The survey responses to Q9, Q10, and Q11 are coded and given as an absolute frequency (the numbers given in brackets) of emerging themes and matched to the categories of the multiple-choice questions (Q1-Q8).*

Survey questions	**Q9. Most effective**	**Q10. Most challenging**	**Q11. Additional comments**
Q1. How effective are the online recorded lectures in helping you understand the course concepts?	lectures (6)	lectures (2)	more live lectures (1)
Q2. How well do you think the hands-on lab project enables you to apply theoretical knowledge to real-world applications?	labs/lab project (5)	labs/lab project 3	more training (1) more equipment (1)
Q3. How effectively do you feel the course facilitates collaboration between students and industry partners through the main challenge (the case)?	Industry (2)	n/a	n/a
Q4. The weekly challenges help me apply theoretical concepts in practical scenarios.	weekly CBL (9)	weekly CBL (8)	n/a

Q5. The interdisciplinary classroom has enhanced my problem-solving skills by exposing me to varied approaches and methodologies.	n/a	n/a	n/a
Q6. The feedback and standard solutions provided after the weekly mini-challenges deepened my understanding of the subject matter.	n/a	n/a	more feedback (1)
Q7. Considering the workload and the learning value, rate how well-balanced you find the distribution of efforts across different course components (lectures, labs, projects):	n/a	time management (4) structure (4)	better grade allocation (2)
Q8. The total workload for this course is appropriate for the credit value.	same as Q7		

Combining the insight from these results, we describe the key findings about student perceptions and experiences.

Effectiveness of online recorded lectures (Q1)

The majority of students (17 responses) rated the online recorded lectures as "somewhat" to “great deal” effective in helping them understand course concepts (Fig. 3). In the words of one of the students: “*Video Lectures and the adaptive questions that test the students' knowledge before proceeding to the next chapter is great!!*”

The lectures were also listed as the second most effective part of the course in the open-ended question (6 responses), while some found them challenging to understand (2 responses) (Table 4). This suggests that while the lectures are beneficial, there might be room for improvement to increase their effectiveness further. For some students, the recorded format was not as engaging and comprehensive, and those students suggested more live lectures: “*I would also like one more lecture every week (...) because this gives you the opportunity to ask questions and understand the information a little bit better*.”

Hands-on labs and the main challenge (Q2)

A significant number of students (18 responses) found the lab projects to be somewhat to very effective, indicating strong practical benefits for many (Fig 3): “*The research proposal is a fun setup. It's cool that you get to make up your own experiments and do them*.”

While our survey question bundled the lab work together with the work on the main challenge, analyzing the students' responses to the open-ended survey questions revealed that they view the lab work as a distinct component (because the work on the challenge also involves literature research and discussions with the industry). The work in the labs was identified as one of the more effective elements of the course in the open-ended question (5 responses), while some found them challenging to understand (3 responses). Suggested improvements (from the optional question) relate to more training in using some of the equipment and providing extra equipment (Table 4).

Collaboration with industry (Q3)

Collaboration with the industry through the main CBL challenge was rated as very effective by a large fraction of students (14 participants): *"I really like the combination with the industry throughout the project. Also the practical way of thinking about the solitions for the CBL really give some hands on exp*erience."

Application of theoretical concepts through mini-challenges (Q4)

The students perhaps had the most mixed feelings towards the weekly mini-challenges. They were largely viewed positively, with 13 students (Fig. 4) agreeing that they help apply theoretical concepts in practical scenarios: "*The CBL presentations every Thursday give us an opportunity to understand the approach the fellow students followed and teaches us something we may not have found ourselves. It makes it easy for me to remember concepts after listening to the different speaks present their respective solution*."

Also, nine students identified them as the most effective element of the course, while 8 students identified them as the most challenging part of the course (Table 4). One student wrote: "*Preparing for the CBL*" for the most effective part (Q9) and "*Also preperation of the weekly CBL but you learn a lot from it*." for the most challenging part (Q10). The issue seems to be related to the workload expected in the course (see Q7 and Q8 below).

Interdisciplinary classroom (Q5)

A balanced distribution of responses to this question showed that some students (9) agreed the interdisciplinary classroom enhanced their problem-solving skills, with a big portion (7) choosing also a neutral stance, implying a lack of strong opinion on the matter (Fig. 4).

Effectiveness of weekly feedback (Q6)

Responses were evenly distributed, with many students agreeing (9) or remaining neutral (5) about the effectiveness of feedback and standard solutions provided after the weekly mini-challenges (Fig. 4).

Balance of the workload (Q7 & Q8)

Student opinions on the balance of workload were divided, with notable frequencies for "not at all" and "little" (10) vs "somewhat" and "much" (11) (Fig. 3). This result highlights that perceptions of workload appropriateness can vary based on individual experiences and expectations. This distribution suggests that while some students find the balance manageable, others felt that the workload distribution could be improved for a more effective learning experience. The students cited issues with time management and course structure (Table 4): *"There just too many other parts of this course, so you are constantly switching between all the different parts. Therefore, it is hard to dive really in all the parts en understand everything very well."*.

The majority of the students (10) disagreed on some level that the total workload for the course was appropriate for the credit value (Fig. 4): *"The [weekly] CBLs are really useful but for 5 presentations it is only 10 percent and that is not enough for the amount of work."*

Insights from the focus group

The focus group session revealed significant insights into students' perceptions and experiences of the microfluidics course implemented using the CBL approach. Building on the issues identified from the survey analysis, we grouped the findings from the focus group under the three key themes:

Fine-tuning course components

Students expressed concerns over the distribution and timing of different course components—lectures, labs, projects, and self-directed work. Some students felt overwhelmed with the amount of work and wanted more attention to the main CBL projects. They felt that they did not have enough time to fully engage with weekly mini-challenges (as expressed in the survey as well), and some felt rushed during presentations and discussions. The students in the focused group highlighted the main CBL projects as the most enriching and relevant learning experiences, suggesting that these should be prioritized and given more time within the course structure. Students appreciated the support and guidance from the TAs and the opportunity to ask questions during lab sessions. They also mentioned the need for more training and instruction for the lab component, especially for using specific equipment or materials (as expressed in the survey, see Table 4).

Aligning instructions and expectations of the CBL project

Another significant concern related to the clarity of instructions and the definition of expectations for the main CBL project component of the course. Students wanted more information about the specific parameters and experimental resources available for their projects. In some cases, there was a noted discrepancy between the expectations set by the academic aspects of the course and the practical demands of the industry partners. Students suggested having a clearer understanding of the project earlier on, including discussions with the industry representatives and more detailed information on available resources, which would aid in navigating the projects more effectively. Overall, however, the students valued the opportunity to work on real-world projects and help companies. This feedback about the course was not so evident from the survey data, which further highlights the benefits of the mixed-method research approach applied here.

Preference for class interactions

The participants expressed a strong preference for more interactive and live lecture formats. The use of pre-recorded videos, while helpful, was reported to be less engaging compared to live sessions. Students valued the immediate feedback and dynamic interaction offered by live lectures, which facilitated a more stimulating and responsive learning environment. While still finding the recorded lectures useful, they suggested also delivering more content via the live lectures to enhance motivation and provide opportunities for real-time discussions and query resolution (as expressed in the survey, see Table 4).

Instructors' reflections and the next steps

The instructors were able to implement a CBL approach in the course in a relatively short time, as they had a clear learning objective-driven focus and previous experience with the CBL-based courses. Their approach was fuelled by empathy (*"If I were a student in this course, would x help me to reach learning objective y within the given time?"*) and a temporary lager focuses on the educational task rather than their research work. In this way, they could still use the latest developments in the field as examples (in the lectures and mini-challenges). In this regard, industry partners contributed greatly to this goal, as their work entails cutting-edge research as well. These efforts were seen and appreciated by the students.

The setup of the course fostered knowledge transfer between the students who are at different departments and different phases of education (the Bachelor and Master level). The instructors observed that the students from different teams actively contributed to the discussions during the mini-challenge presentations. The adoption of this approach resulted in the involvement of more diverse student groups in collaboratively constructing knowledge on the topics of study.

As a result of the focus group co-creation session with the students, the instructors decided to make all the mini-challenges last two weeks to allow for a deeper dive into a few topics in order to help students navigate the complexity of the theory while still developing creative research skills. The mini-challenges would also include a short written reflection so that the students get individualized feedback on their understanding of the work done in a team, in addition to team-level feedback that they get on their presentation of mini-challenges.

Conclusion

The implementation of the CBL approach in the Lab on a Chip/Microdevices (LOCM) course represents a significant shift from traditional teaching methods to a more interactive and practical learning environment. Here we summarize the key findings from the quantitative and qualitative evaluations to highlight the successes and challenges of this pedagogical innovation.

The quantitative data indicate that the hands-on lab projects were particularly effective, with many students rating them highly for practical learning. This aligns with the core characteristic of CBL, which emphasizes the real-world application of theoretical knowledge (e.g., Kohn Rådberg et al. 2020). Students' positive feedback on the practical components of the course suggests that integrating hands-on projects with theoretical instruction can significantly enhance understanding and retention of complex concepts in microfluidics. Studies have shown that challenge-based instruction can improve student performance, especially on more difficult questions, compared to traditional lecture-based instruction (Roselli & Brophy 2006; Membrillo-Hernández et al. 2021). The integration of industry projects within the CBL framework has been pivotal in providing real-world context and enhancing the relevance of the learning experience. This aspect is supported by the work of Clegg and Diller (2018), who found that CBL promotes students’ development of transferable frameworks and confidence in engineering problem-solving. The practical benefits of hands-on labs and industry collaboration, as highlighted by our students, reinforce the value of authentic, real-world challenges in engineering education. Effective collaboration enhances teamwork and academic performance (e.g., Park et al. 2015). However, managing such diversity also poses challenges in terms of aligning expectations and ensuring that all students are adequately prepared for the course's demands.

Despite its benefits, CBL implementation comes with challenges. The time management in the course and preparation for weekly mini-challenges were noted as significant challenges. This feedback indicates that while CBL is effective in principle, its success depends heavily on the logistical and instructional support provided to students, which aligns with previous research. For instance, Mesutoglu et al. (2024) noted that clear instructions and adequate resources are crucial for the successful execution of CBL projects. They emphasized the importance of aligning academic and practical demands to ensure students can effectively navigate their projects.

Student responses regarding workload balance were mixed, indicating variability in individual experiences and expectations, which is especially relevant for courses like this with not just a different discipline background but also year level. While some students found the workload appropriate for the credit value, others felt it was too demanding. Furthermore, the students' preference for more live lectures over pre-recorded videos highlights the need for dynamic interaction and immediate feedback to enhance engagement and comprehension. While the recorded lectures were useful, students suggested that additional live sessions could significantly improve their learning experience by providing real-time discussions and query resolutions. Research indicates that aligning student expectations with course demands can improve self-regulated learning and academic outcomes (Rovers et al. 2018). Adjusting the course design to ensure a more balanced distribution of tasks and clear communication of expectations could address these concerns.

Thus, while the mixed-method approach provides valuable insights, the study could be improved by collecting more demographic data and differentiating data from bachelor and master students, thus accounting for their varied disciplinary backgrounds. This approach might provide more granular data to better understand the mixed feedback and ensure the CBL approach is equitably effective across diverse student populations.

Instructor observations confirmed that the CBL approach fostered knowledge transfer among students from different disciplines and educational levels. This vertical integration not only enhanced the learning experience but also prepared students for the collaborative nature of professional environments. The emphasis on empathy and student-centered design in the course planning and re-designing process was crucial in addressing the diverse needs of the interdisciplinary cohorts in this course. These observations suggest that the instructor's role in CBL is pivotal, requiring a balance of facilitator, mentor, and content expert.

In summary, the implementation of the CBL approach in our course has provided valuable insights into the efficacy of this pedagogical approach in higher education, particularly within interdisciplinary fields like biomedical engineering. Our quantitative and qualitative data indicate that students largely benefited from the CBL approach. The high ratings for the practical components of the course underscore the importance of experiential learning in technical disciplines, supporting the argument for incorporating more practical, challenge-based elements in engineering curricula. Students' feedback also highlighted a desire for more detailed guidelines and support. This suggests that while CBL promotes autonomy and problem-solving skills, it also requires a well-structured framework to ensure that students are not overwhelmed. The balance between providing autonomy and sufficient support is crucial in maximizing the benefits of CBL.

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Notes on Contributors

Burcu Gumuscu is an assistant professor at Eindhoven University of Technology, specializing in microfluidics for regenerative medicine. Particularly, she is interested in determining cell-specific bioelectricity patterns by taking advantage of digital microfluidics.

Lanhui Li is a postdoc in the Biosensors and Devices Lab at the Department of Biomedical Engineering, Eindhoven University of Technology. Her research focuses on the development of Microfluidic platforms for chemical and biological assessment.

Kalpit J. Bakal is a PhD candidate in the Microsystems Section at the Department of Mechanical Engineering, Eindhoven University of Technology. His research focuses on developing a technique to characterize the viscoelastic properties of soft objects at microscopic scales.

Oscar M.J.A. Stassen is a postdoc in the Microsystems Section, at the Department of Mechanical Engineering, Eindhoven University of Technology. His research focuses on the effects of mechanical stimuli on biological cells, by integrating dynamic cellular reporter systems with microfabricated systems.

Hans M. Wyss is an associate professor in the Microsystems section, at the Department of Mechanical Engineering, Eindhoven University of Technology. Hans' group develops and uses microfluidics tools for studying and controlling the behavior of soft and biological materials.

Jasmina Lazendic-Galloway is an astrophysicist with a passion for learner-centered and evidence-based teaching practices and has an extensive experience in interdisciplinary teaching and professionalization of teaching in higher education. She is currently an interdisciplinary research fellow at the TU/e Innovation Space, which is a center of expertise for challenge-based learning and entrepreneurship education at Eindhoven University of Technology.

References

Anderson, L. W. and Krathwohl, D. R., et al (Eds.) (2001) A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. Allyn & Bacon. Boston, MA (Pearson Education Group)

Andersson, H., & Van Den Berg, A. (2004). Microfabrication and microfluidics for tissue engineering: State of the art and future opportunities. Lab on a Chip, 4(2), 98-103 https://doi.org/10.1039/B314469K

Bezrukov, A., Sultanova, D. (2021). Application of Microfluidic Techniques to Experimental Research of Engineering Students. In: Auer, M.E., Rüütmann, T. (eds) Educating Engineers for Future Industrial Revolutions. ICL 2020. Advances in Intelligent Systems and Computing, vol 1329. Springer, Cham. https://doi.org/10.1007/978-3-030-68201-9_85

Biggs, J. (1996). Enhancing teaching through constructive alignment. High Educ 32, 347–364. https://doi.org/10.1007/BF00138871

Boud, D. (2016). Taking Professional Practice Seriously: Implications for Deliberate Course Design. In: Trede, F., McEwen, C. (eds) Educating the Deliberate Professional. Professional and Practice-based Learning, vol 17. Springer, Cham. https://doi.org/10.1007/978-3-319-32958-1_11

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative research in psychology, 3(2), 77-101.

Case, J. M., & Light, G. (2011). Emerging research methodologies in engineering education research. Journal of Engineering Education, 100, 186-210. https://doi.org/10.1002/j.2168-9830.2011.tb00008.x

Choi, N. W., Cabodi, M., Held, B., Gleghorn, J. P., Bonassar, L. J., & Stroock, A. D. (2007). Microfluidic scaffolds for tissue engineering. Nature Materials, 6(11), 908-915. https://doi.org/10.1038/nmat2005

Clegg, J. R., & Diller, K. R. (2019). Challenge-based instruction promotes students' development of transferable frameworks and confidence for engineering problem solving. European Journal of Engineering Education, 44(3), 398–416. https://doi.org/10.1080/03043797.2018.1524453

Coulson, D., & Harvey, M. (2013). Scaffolding student reflection for experience-based learning: A framework. Teaching in Higher Education, 18, 401-413. https://doi.org/10.1080/13562517.2012.752726

Gallagher, S. E., & Savage, T. (2020). Challenge-based learning in higher education: an exploratory literature review. *Teaching in Higher Education*, *28*(6), 1135–1157. https://doi.org/10.1080/13562517.2020.1863354

Gibbs, P., Cartney, P., Wilkinson, K., Parkinson, J., Cunningham, S., James-Reynolds, C., Zoubir, T., Brown, V., Barter, P., Sumner, P., MacDonald, A., Dayananda, A., & Pitt, A. (2017). Literature review on the use of action research in higher education. *Educational Action Research*, 25, 22 - 3. https://doi.org/10.1080/09650792.2015.1124046

Haenen, J., Vink, S., Sjoer, E., & Admiraal, W. (2024). Challenge and learning in honours education: a quantitative and qualitative study on students' and teachers' perceptions. Teaching in Higher Education, 29, 216-232. https://doi.org/10.1080/13562517.2021.1973408

Harris, T., Bransford, J., & Brophy, S. (2002). Roles for learning sciences and learning technologies in biomedical engineering education: a review of recent advances. *Annual review of biomedical engineering*, 4, 29-48 https://doi.org/10.1146/ANNUREV.BIOENG.4.091701.125502

Kember, D., & Gow, L. (1992). Action research as a form of staff development in higher education. *Higher Education*, 23, 297-310. https://doi.org/10.1007/BF00145018

Khademhosseini, A., & Langer, R. (2016). A decade of progress in tissue engineering. Nature Protocols, 11(10), 1775-1781. https://doi.org/10.1038/nprot.2016.123

Kohn Rådberg, K., Lundqvist, U., Malmqvist, J., & Hagvall Svensson, O. (2020). From CDIO to challenge-based learning experiences – expanding student learning as well as societal impact? European Journal of Engineering Education, 45(1), 22–37. https://doi.org/10.1080/03043797.2018.1441265

Lazendic-Galloway, J., Laszlo, I. Schliephake K. and Baird, M. (2020), Developing students' reasoning skills through reflective lab assessment, 31st Annual Conference of the Australasian Association for Engineering Education (AAEE 2020): Disrupting Business as Usual in Engineering Education, p. 422–429

Lazendic-Galloway, J., Reymen, I.M.M.J., Bruns, M., Helker, K., & Vermunt, J.D. (2021), Students' experiences with challenge-based learning at TU/e innovation Space – overview of five key characteristics across a broad range of courses. In H-U. Heiß, H-M. Järvinen, A. Mayer, & A. Schulz (Eds.), Blended Learning in Engineering Education: challenging, enlightening – and lasting? Proceedings of the SEFI 49th Annual Conference, p. 1005-1015

Low, L.A., Sutherland, M., Lumelsky, N.L., Selimović, Š., Lundberg, M.S., & Tagle, D.A. (2020). Organs-on-a-Chip. *Advances in experimental medicine and biology*, *1230*, 27-42. https://doi.org/10.1007/978-3-030-36588-2_3

McLellan, H. (Ed.). (1996). Situated learning perspectives. Englewood Cliffs, NJ: Educational Technology Publications.

Membrillo-Hernández, J., de Jesús Ramírez-Cadena, M., Ramírez-Medrano, A. *et al.* (2021). Implementation of the challenge-based learning approach in Academic Engineering Programs. *Int J Interact Des Manuf* 15, 287–298. https://doi.org/10.1007/s12008-021-00755-3

Mesutoglu, C., Bayram, D., Vennix, A., Limburg, A., & van der Veen, J. (2024). Boundary interactions of applied physics and mechanical engineering students in a challenge-based learning course. European Journal of Engineering Education, 1–17. https://doi.org/10.1080/03043797.2024.2326438

Montesinos, L., Salinas-Navarro, D.E. & Santos-Diaz, A. Transdisciplinary experiential learning in biomedical engineering education for healthcare systems improvement. *BMC Med Educ* **23**, 207 (2023). https://doi.org/10.1186/s12909-023-04171-x

Park, H., Kim, C., Park, J., & Park, E. (2015). Effects of team-based learning on perceived teamwork and academic performance in a health assessment subject.. Collegian, 22 3, 299-305 . https://doi.org/10.1016/J.COLEGN.2014.05.001

Perna, S., Recke M.P. & Nichols, M.H. (2023). Challenge Based Learning: A Comprehensive Survey of the Literature. The Challenge Institute. https://www.challengeinstitute.org/CBL_Literature_Survey.pdf

Roselli, R., & Brophy, S. (2006). Effectiveness of Challenge-Based Instruction in Biomechanics. Journal of Engineering Education, 95. https://doi.org/10.1002/j.2168-9830.2006.tb00906.x

Rovers, S., Clarebout, G., Savelberg, H., & Merriënboer, J. (2018). Improving student expectations of learning in a problem-based environment. Comput. Hum. Behav., 87, 416-423. https://doi.org/10.1016/j.chb.2018.02.016

Salmon, G. (2012). *E-moderating: The key to online teaching and learning*. Routledge. https://doi.org/10.4324/9780203816684

Schreiber, L., & Valle, B. (2013). Social Constructivist Teaching Strategies in the Small Group Classroom. *Small Group Research*, 44, 395 - 411. https://doi.org/10.1177/1046496413488422

Singh, A., Ferry, D., & Mills, S. (2018). Improving Biomedical Engineering Education Through Continuity in Adaptive, Experiential, and Interdisciplinary Learning Environments.. *Journal of biomechanical engineering*, 140 8. https://doi.org/10.1115/1.4040359

Wikswo, J., Block, F., Cliffel, D., Goodwin, C., Marasco, C., Markov, D., McLean, D., McLean, J., McKenzie, J., Reiserer, R., Samson, P., Schaffer, D., Seale, K., & Sherrod, S. (2013). Engineering Challenges for Instrumenting and Controlling Integrated Organ-on-Chip Systems. *IEEE Transactions on Biomedical Engineering*, 60, 682-690. https://doi.org/10.1109/TBME.2013.2244891

Yuen, K., & Hau, K. (2006). Constructivist teaching and teacher-centred teaching: a comparison of students' learning in a university course. *Innovations in Education and Teaching International*, 43, 27