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Learning through projects and practical work

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Foreword

Learning through projects – Preparing for a future we do not yet know

The world is changing rapidly, bringing with it challenges that we and future generations will face. But how do we prepare our students today to solve the problems of tomorrow, problems that we cannot yet foresee? This calls for an education that is grounded in the latest research concerning higher education, and that goes beyond the mere transmission of specialised knowledge. Our students must learn to develop viable solutions for complex problems both within and across disciplines. For this, they need a broad set of competencies that enable them to integrate various perspectives, navigate uncertainty, and collaborate successfully.

An effective way to strengthen these skills is through project-based education that is at the heart of our *Vision for Teaching at ETH Zurich*. This educational approach immerses students in relevant, practice-oriented contexts where they apply their expertise, critically examine their knowledge, and collaboratively develop new ideas. In both subject-specific and interdisciplinary courses, students quickly realise that simple answers are rare – yet asking the right questions is often the first step towards meaningful solutions.

Commitment to excellent teaching

Project-oriented, competency-based, and individualised learning is challenging – not only for students but also for lecturers. It demands a high level of commitment, motivation, and the ability to adapt their role flexibly to students' needs. Alongside deep subject-matter expertise, strong didactic competencies and supportive supervision are essential to guiding students on their individual learning paths and promoting critical engagement with what they have learned. Moreover, students themselves often take on an active role in teaching, for example, by coaching student teams or moderating specific teaching sequences.

In this issue of the *ETH Learning and Teaching Journal*, lecturers share insights into the courses they have designed, implemented, and continuously refined with great passion and dedication. Their experiences show how project-based education is embedded at ETH Zurich, as an integral part of a world-class university education that not only empowers students but also strengthens ETH Zurich as a leading institution in higher education.

A shared commitment to learning

I hope this edition of the journal inspires you – the teaching community at ETH Zurich and other research-intensive universities. I am inviting you to discover new perspectives and explore ways to develop your own approaches to project- and practice-oriented teaching. Let's shape the future of learning together – at ETH Zurich and beyond.

Prof. Dr. Günther Dissertori
Rector of ETH Zurich

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Editorial

The world is changing rapidly, bringing with it complex scientific, technical, ecological, economic, and societal challenges – challenges that our graduates must be prepared to face and solve. Today, graduates require not only deep expertise in their subject areas but also broader competencies – such as problem-solving, critical thinking, and adaptability - that enable them to effectively engage with real-world problems across disciplines. In response, Project-Based Education (PBE) connects theoretical insights and practical experiences. This strong connection between solid foundations and practical application promotes the range of competencies that students will require to make valuable contributions to science, industry and society. This issue of the ETH Teaching and Learning Journal, titled *'Learning through projects and practical work: Preparing students for a future we do not yet know',* places project- and practice-based education into the spotlight.

Learning through projects and practical work has a long and distinguished tradition at ETH Zurich, dating back to its foundation in 1855. Elsner et al. highlighted several teaching initiatives, such as the *Projektorientierter Studiengang* (POST) from the 1970s or *River Restoration*, a recently redesigned project-based course, that exemplify this tradition and provide a framing of Project-Based Education (PBE) for ETH Zurich in this issue. Recognizing the enduring relevance of this educational model, the Rector reaffirmed the commitment to project-based teaching and learning by designating it as a strategic teaching initiative in 2022, leading to the establishment of PBLabs (Project-Based Labs), whose mission is to promote and enable PBE across the university. Project-oriented and competency-based teaching remains central to the Vision for Teaching at ETH Zurich, as exemplified by the excellent teaching practices featured in this journal, each highlighting key aspects of learning through projects.

Project-based courses are embedded in relevant, practice-oriented contexts and closely linked to real-world applications. Several contributions in this issue vividly illustrate how lecturers design their courses to give students a tangible insight into the kinds of challenges and work they may encounter after graduation – whether in designing assistive technologies (Gantenbein & Gassert) or physics experiments (Eggenberger et al.). Other contributions more generally address the design of project-based formats and the integration of real-world practice (Hischier et al.; Dorn et al.).

Other author teams focus on how their courses foster transferable competencies and how they evaluate students' development in this area. Two contributions demonstrate how such competencies can be promoted in very different settings – from large, structured bachelor courses (Köhler & Tobler) to small, agile exploratory projects (Gisler et al.). Another contribution describes the use of Design Thinking as a methodology to cultivate a broad range of methodological and social skills (Benabderrazik et al.). Brüggemann & N'Guyen present an approach to assessing students' competence development through the analysis of written reports.

Embedding projects in real-world contexts often requires extending teaching and learning beyond the traditional classroom. Thurn et al. present an outdoor education project in which students design and implement their own teaching units. Walker et al. demonstrate how a field trip to a museum can help engineering students connect technical knowledge with complex societal contexts. Other contributions explore how external stakeholders can be actively integrated into teaching (Mader et al.), or how virtual representations such as digital twins can simulate real-world environments in urban design education (Pagani et al.).

The last contribution in this issue is an invited contribution. It provides a highly relevant account of how to make Mathematics education scalable (Akveld et al.).

We would like to thank all authors for their valuable contributions to this issue of the *ETH Teaching and Learning Journal*. The diverse experiences shared here illustrate the many facets of project-based education, offering insights and inspiration for teaching practice across disciplines. We hope that their experiences inspire and encourage you – the teaching community at ETH Zurich and other research-intensive universities – to explore and expand your approaches to project-oriented and practice-based education. Let us continue working together to shape the future of higher education, preparing our students to not only navigate but actively contribute to a world full of unknown possibilities and challenges.

Florian Rittiner, Pia Scherrer, Benno Volk
Issue editors

Framing project-based education at ETH Zurich

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Abstract

Universities today walk a complex line between delivering education that is more than just professional training, whilst ensuring that graduates are equipped adequately to navigate post-study employment. One approach to this challenge is to focus on competencies as a way to frame and capture learning that goes beyond classic subject-specific knowledge. This paper explores the potential of project-based education (PBE) as a pedagogic approach relevant for institutions interested in fostering transferable competencies, using the example of ETH Zurich. After introducing the history of PBE, this paper proposes a definition of PBE for ETH Zurich. It discusses the operationalisation of the definition, using guiding questions and sharing examples of PBE that already take place at ETH Zurich. Finally, the paper concludes with a set of implications of PBE for ETH Zurich and more broadly for higher education institutions.

Introduction

Universities are at the forefront of educating and training the researchers and professionals of tomorrow. In a rapidly changing world, graduates must develop the ability to learn and adapt swiftly. Universities play a crucial role in equipping them with knowledge, skills, attitudes while fostering lifelong, critical and reflective learning (Harvey, 2000). Universities today walk a complex line between delivering education that is more than just professional training, whilst ensuring that graduates are equipped adequately to navigate post-study employment (Collini, 2012; La Cara, 2023a). This balancing act is often understood through the lens of ‘missions’: the different, sometimes contradictory aims and expectations of higher education (HE) institutions can be broadly captured under Mission 1 (‘doing research’), Mission 2 (‘doing teaching’), and Mission 3 (‘adding value to society’) (Berghaeuser & Hoelscher, 2020; Etzkowitz & Leydesdorff, 2000).

Teaching, the core of Mission 2, forms a point of connection between the other missions. Universities are in the unique position of selecting and shaping their future employees – the training of future scholars and scientists is intrinsic to the purpose of a university. The way universities teach today influences the abilities of those students that go on into research to plan, undertake and communicate the research of tomorrow – the Mission 1 of universities (Collini, 2012). Universities are also organisations embedded in a broader social context, deeply bound to it via material resources (e.g. funding), and government rules and regulations (Berghaeuser & Hoelscher, 2020). The expectations of universities have grown as society has changed towards a ‘Knowledge Society’, and modern governments and society expect universities to have a higher contribution through innovation, spin-outs, and by promoting life-long learning suited to a changing work context (Enders & De Boer, 2009). Teaching thus bridges both the need for excellent researchers and the need of society for graduates who are capable of supporting the modern workplace and knowledge society.

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Careful consideration of how teaching is done is therefore a crucial activity for universities wishing to navigate these complex, contradictory relationships and requirements. Curricula (the foundation of study/degree programmes) are one of the most important 'products' that a university offers and are profoundly shaped by the specific knowledge field of the academics that deliver the curricula (Barnett et al., 2001). At the same time, since the 1980s there has been a shift in the production and application of academic knowledge, from 'is it true?' to 'what use is it?' (Barnett et al., 2001; Lyotard et al., 1984). This focus on 'use value' has driven changes in curricula, with a move towards including 'competencies' in addition to subject-specific knowledge within curricula (Barnett et al., 2001). Examples of this emphasis on competencies can be observed in medicine (e.g. in the US (Powell & Carraccio, 2018)), chemistry (e.g. in Brazil (Franco et al., 2023)), engineering (e.g. in Russia (Lunev et al., 2013)) and many other. Examples dating back to the mid-1970s (e.g. agricultural science (Mather et al., 1977)), indicate that this approach has been around for a long time.

Competencies can be defined as the combination of knowledge (information developed or learned through experience and study), skills (acquired through repeated application of knowledge or ability) and behaviours (observable reaction of an individual to a certain situation) that are directly related to successful performance (National Institutes of Health, n.d.; United Nations, 2010). Competencies are defined as *knowledge* (what knowledge students acquire in a course, e.g. facts and concepts), *skills* (what the students can do after a course, e.g. procedures and strategies), and *attitudes* (the values or beliefs students can develop in a course) (La Cara et al., 2023b). Someone who is competent is consistently capable of using their body of knowledge, skills and attitude to successfully undertake tasks beyond what was covered within their education programme (Vitello et al., 2021).

Because universities are required to train their future staff to be able to do research (Mission 1) as well as contribute well-educated future employees to a society that is changing and increasingly in need of knowledge workers (Mission 3), competencies have the potential to serve both purposes. Transferable competencies[2] are a cross-cutting set of skills, knowledge and attitudes that support students to apply subject-specific knowledge during their studies (La Cara, 2023a) and across a lifetime (European Union, n.d.). Examples of transferable competencies include: problem-solving and decision-making, working in teams and collaborating, project and self-management, communicating and negotiating, critical and creative thinking, and technology and information literacy amongst others. Fostering these competencies is increasingly seen as an essential requirement of advanced degrees and must be given in context i.e. cannot be separated from subject-specific competencies (La Cara et al., 2023a).

Higher education institutions are challenged today in how they teach to ensure that transferable competencies in addition to subject-specific competencies can be developed. This paper investigates the potential for a specific pedagogic approach, project-based education (PBE), as a way to frame and strengthen the acquisition of transferable competencies within the student body using the example of ETH Zurich. This paper defines and operationalizes PBE, building on the existing ETH Competence Framework (La Cara, 2023a) to illustrate what project-based education is and how it fosters students' transferable competencies.

A brief history of PBE at ETH Zurich

Today's project-based education can trace its roots back to the post-Enlightenment European art and architecture Academies. The Académie des Beaux-Arts[3] established in 1648 in Paris developed a teaching style where students learned from a Master with the aim of imitating his[4] approach on developing an architecture project in a real-world context. Each student would

[2] Transferable competencies are also known as transversal skills or 21st century skills. Depending on the context, they typically combine social and personal competencies as well as method-specific competencies.
[3] and later in 1863 renamed into École des Beaux-Arts
[4] Women were admitted beginning in 1897.

choose an 'atelier' run by his desired master which he would stay with until the end of his studies. Each atelier was characterized by the small number of students and hence, greater attention by the teacher. In this group, students would work individually on their six design projects which they completed over a period of five weeks to three months (Chafee, 1977). Based on the public competition system in practice, students would defend their thesis design project in a lengthy oral examination in front of a prominent jury (Salama, 2015). Ever since, architectural education has been strongly based on this pedagogical model of design teaching in the design class (also referred to as studio or atelier). Typical characteristics of design teaching such as 1) navigating a complex and open-ended problem while tackling heterogeneous issues, 2) expressing design proposals in various media, 3) passing through multiple and rapid iterations within semester length projects, and 4) earning frequent critique in both formal and informal set-ups are typical features of the culture in architecture studio teaching (Kuhn, 2001).

This project-based learning approach was established at ETH Zurich[5] from its foundation in 1854 to boost technical education in the newly formed Swiss Confederation. On October 15, 1855, Gottfried Semper founded the Bauschule[6] as one of six departments at the Polytechnikum (the original name of ETH Zurich). As a proven Baukünstler and theorist, he reformed the tightly organized structure of polytechnic teaching for his discipline. Drawing on his experiences as a professor at the École des Beaux-Arts in Dresden from 1834 to 1854, he translated its model of project-based education to his own in Zurich (Tschanz, 2015). Through this, he would prepare his students for their later work in practice. Since the founding of the Architecture school, the model of architecture education at ETH Zurich, especially the design studios, has remained basically the same.

Project-based education globally found its verbal expression, recognition in education science and application within other disciplines beyond architecture later in the early 20th century. In 1918, an essay was published by the American pedagogue William H. Kilpatrick (1918), entitled 'The Project Method' (Kilpatrick, 1918), which caught the attention of US educators and drew focus onto the importance of student engagement in learning, a key element of project-based education today (Larmer et al., 2015). This contrasted with dominant assumptions at the time about how learning occurred. Until about the 1950s, the dominant theory of learning, called 'Instructionism', assumed that knowledge was deposited into the heads of students by teachers or lecturers through lecturing and demonstration. It emphasised factual learning and rote memorisation (Sawyer, 2022).

However, since at least the 1900s, educators in polytechnical education had proposed alternatives to this theory, and as education science and observations of learning have become a field of research, it has become evident that students (indeed, all learners) construct their knowledge through experience – the so-called 'Constructivist' theory of learning (Sawyer, 2022). By the 1960s, many educators were pushing back on Instructionist-informed education approaches, with authors like the Brazilian educator and philosopher Paulo Freire (1970) advocating for active and participatory didactic approaches. He wrote about 'problem-posing education' – the foundations to develop transferable competencies (Freire, 1970). Higher education institutions established in the 1970s, like McMaster University, Roskilde University and Aalborg University, began to test new approaches to higher education emphasising smallgroup, self-directed and problem-based education (Servant-Miklos, 2019).

At ETH Zurich, students demanded reform of how teaching was delivered in the 1970s. A new curriculum was designed for advanced students, the Projektorientierter Studiengang (POST). This moved away from traditional frontal teaching and towards more active student participation and real-world connection. This was co-designed with lecturers and students and hosted in the Abteilung für Naturwissenschaft (Department of Natural Sciences, today called

[5] ETH Zurich is a federal university in Switzerland; https://ethz.ch/en.html
[6] In 1899, the Bauschule was renamed Architekturschule, and in 1924, it became the Department of Architecture.

Department for Environmental Systems Science, or D-USYS). POST was a radical departure from typical ETH Zurich teaching at that time. It completely rethought the content and form of study with an emphasis on interdisciplinarity across teaching, research and didactics. Its intention was to give students an understanding of research through teaching (Gugerli, 2005). POST was discontinued after 15 years for a variety of reasons (Gugerli, 2005), although its essence lives on in the teaching at D-USYS within specific modules like the year-long Umweltproblemlösen (solving environmental problems) bachelor's course (Pohl et al., 2020).

In 2022, ETH Zurich decided to build anew on its background in project-based education, and its strong tradition of preparing students of careers in research and industry. It established PBLabs (Project-based Labs) to promote and enable project-based education across the institution and encourage more competence-oriented teaching and especially to foster transferable competencies. PBLabs supports lecturers in developing and implementing project-based formats and helps students acquire specific transferable competencies, such as coaching and facilitation skills.

ETH Zurich's definition and approach to PBE

Terminology around PBE in practice and in academic literature can be confusing for practitioners (Servant-Miklos, 2020). There are many terms in use around this style of teaching, including: problem-based education (Denayer et al., 2003), problem-based learning (Winning & Townsend, 2007), practice-based education (Mann et al., 2020), challenge-based learning 'CBL' (Sukackė et al., 2022), case study learning (Savery, 2006), project-oriented studies (Lee et al., 2014), inquiry-based learning (Larmer et al., 2015), project-based learning and problem-based learning (De Graaff & Kolmos, 2003; Krajcik & Blumenfeld, 2006; V. Servant-Miklos, 2020, V. F. C. Servant-Miklos, 2019). This broad range of terms encompass the following key aspects: active teaching styles or learning techniques (strongly focused on engaging students directly in the learning process), mixed educational approaches, a commitment to interdisciplinarity, the promotion of self-directed learning, encompassing group work and a focus on the real-world connection.

Higher education institutions like ETH Zurich, because of different disciplines and teaching methodologies, require a shared understanding of and language for pedagogical approaches. ETH Zurich spans 16 departments, over 70 bachelor's and master's programs, and various continuing education formats, so selecting a broad yet precise term is crucial. PBLabs therefore made dedicated effort to develop a practical, institution-wide definition to ensure clarity and consistency in how project-based education is implemented at ETH Zurich. The definition was based on a literature review and multiple discussions with members of ETH Zurich (including educational developers, members of the of the Unit for Teaching and Learning, and lecturers).

The term 'Project-Based Education' (PBE) was chosen because it accommodates the wide range of courses incorporating project elements, allowing for flexibility in interpretation while maintaining conceptual coherence. Furthermore, the term 'education' emphasizes the integral relationship between teaching and learning, reinforcing that project-based formats are not just about active learning (the foundations to develop transferable competencies) but also structured educational design. The following section presents a detailed definition of project-based education at ETH Zurich, outlining its key features.

Definition:
Project-Based Education (PBE) is a pedagogic approach that uses project work to foster subject-specific and transferable competencies, as well as independent learning. Students typically work in teams, sometimes with a guide/coach, and are given a challenge situated in a practice-based context. Through independent inquiry and research (both individually and as part of a group), as well as with a variety of inputs (such as lectures and expert visits), students develop problem statements and solutions that are presented at the end of the course.

Key Features: Under the term ‘project-based’, we recognise that there are many varieties of projects and many methods that can be applied within projects. Across this diversity, however, there are some core principles (see Figure 1):

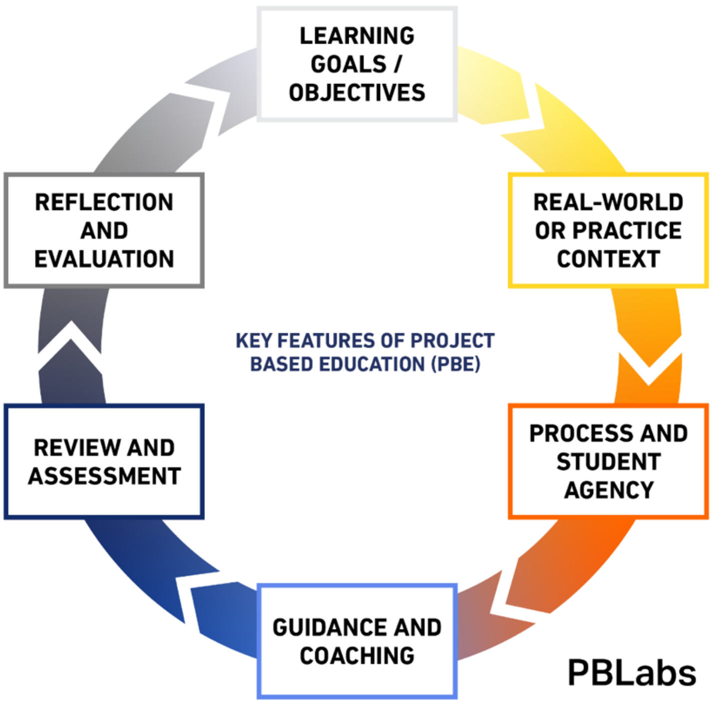

Figure 1: The key features of project-based education (PBE).

Learning objectives

The project is central to the course’s curriculum, i.e. students learn a substantial part of the content through the project. Lecturers design learning objectives that clearly connect the content of the course to the subject-specific and transferable competencies that students are expected to develop during the course.

Real-world or practice context

The lecturer(s) situate the project in a relevant, practice-based context, often with connection to practitioners or communities outside the academic context (e.g. as project partners, experts or reviewers). Students navigate a complex and open-ended problem while considering manifold perspectives in their solution-finding process.

Process and student agency

The project offers students a degree of freedom in the definition of a problem/situation, the project process and/or the development of the outcomes of the project. Students pass through multiple and rapid (design/development) iterations. The project promotes independent inquiry and exploration and through this stimulates agency and piques curiosity.

Guidance and coaching

Students often collaborate in (interdisciplinary) groups. Coaches moderate the team process. The lecturers facilitate the learning process by providing guidance and prompting the groups or individuals to find solutions independently. Experts may be invited to provide subject-matter insights, feedback and reviews. Depending on the project size and structure, the roles of the lecturer, coach, and expert may be fulfilled by multiple individuals or the same person.

Review and assessment

Students undertake formative assessments throughout the project and produce a final result that is typically presented to peers and (ideally) external stakeholders from the practice context. Assessments are graded such that both subject-specific and transferable (including method-specific) competencies are assessed. Often, assignments are tailored to the real-world context, such that students use a variety of media to visualize their project as well as process.

Reflection and evaluation

The lecturers design and deliver the project in a way that students are encouraged to reflect on their own learning journey and can understand how both subject-specific and transferable competencies are fostered through the project.

Operationalising the approach

Project-based education is a practice that must be tried out, reflected upon and improved – much like any sort of teaching. In the following section, the above definition and core principles are reconfigured to encourage and support readers to engage with them, and particularly to promote the inclusion of PBE elements into existing teaching practice as well as pedagogical concepts such as Constructive Alignment (Biggs, 1996).

Understanding how the core principles relate to each other is a fundamental aspect of designing a good PBE experience. Whilst the different elements interact across the circle in Figure 1, when designing a PBE format typically the elements are planned in the order shown: First, the main learning objectives of the class and a real-world context needs to be agreed on. Then, more detailed elements such as coaching, assessment, or reflection can follow in the planning process. In this way, Figure 1 aligns with the course design process captured by which forms an excellent introduction to course design for those with little experience.

The cyclical nature of the principles is also important. Most classes at ETH Zurich are part of a curriculum and offered multiple times, providing opportunities to test, gain experience, collect feedback, refine and implement again. In PBE, the overall format may be reasonably consistent although the real-world or practice context or external partners may change.
The PBE cycle can be easily integrated with the Constructive Alignment approach (Biggs, 1996). This pedagogical concept suggests that learning objectives, learning experience and assessment need to be carefully aligned with each other.

As Figure 2 shows, this maps neatly onto the PBE core principles: This suggests that assessment should be heavily informed by the learning objectives to make sure that what is tested is in fact producing the desired learning. At the same time, assessment should reflect/support the student learning experience including the real-world context, the learning process, the guidance and coaching that they receive, and the space for reflection.

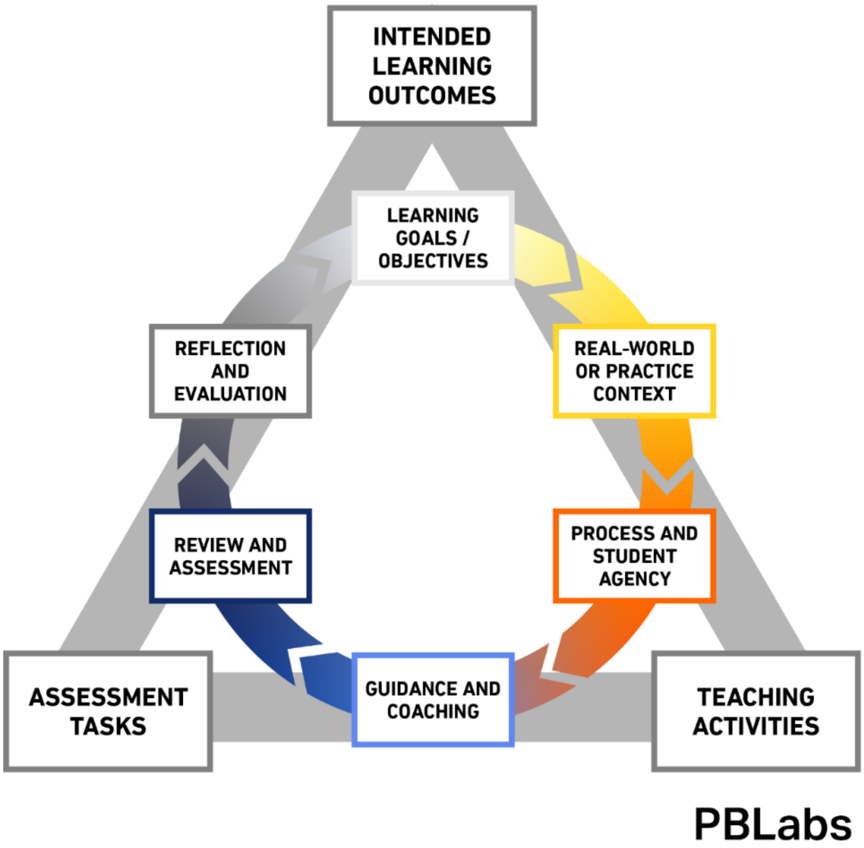

Figure 2: Key features of PBE mapped against the concept of Constructive Alignment. Teaching and learning activities are included the real-world or practice context, the process and student agency as well as the guidance and coaching.

Guiding questions for implementing PBE at ETH Zurich

To support the operationalization of the definition of PBE, the following ‘guiding questions’ are offered. These questions are intended to help those involved in designing and delivering a module to think carefully about how to engage with the different aspects of PBE. It is important to note that there is no one-size-fits-all approach to designing PBE formats. The guiding questions, and examples in this paper aim to serve as inspiration for those interested in introducing PBE elements to classes. As with any teaching, but perhaps especially when committing to project-based formats which often involve external guests, site visits, etc., it is important to take resources into account at an early stage in the design process. Thus, we also include additional guiding questions for anyone designing a class. These are not considered in the examples listed below but should be a central part of any course design discussion.

Learning goals/objectives	▪ What are the main subject-specific knowledge and transferable competencies that students should learn through this project?[7]
Real-world or practice relevance/ context	▪ How is the project embedded into the curriculum? ▪ What is the connection to a real-world or practice/industry context? ▪ Which challenge or situation can students address through the project?

[7] See more on how to write competence-based learning objectives here: https://ethz.ch/content/dam/ethz/main/eth-zurich/education/lehrentwicklung/files_EN/Vorlage_LernzieleFormulierenEn.pdf

Process and student agency	▪ What options do students have in the design and delivery of the project? ▪ How does the project support students to work independently and develop their own learning journey?
Guidance and coaching	▪ What support is offered to students and when throughout the project? ▪ Who gives this support, and what preparation or training do they need?
Review and assessment	▪ How do students present their work to an audience which could include peers, faculty and external members from the real-world/practice context? ▪ How is formative assessment used? ▪ How are assessments designed to assess the subject-specific and transferable competencies mentioned in the learning objectives?
Reflection and evaluation	▪ How can students explain how the project fostered their transferable and subject-specific competencies? ▪ What space can be given within the project to reflection and feedback on the project journey, the results and teamwork?
Resources	▪ Who needs to be involved to deliver the core content? ▪ What locations or teaching spaces will be needed for this project? ▪ What is the budget for the project's delivery?

Table 1: Guiding Questions for Designing Project-Based Formats.

Examples of PBE in action at ETH Zurich

Example 1 – Entrepreneurship: This course is notable for the very large class size, and the strong connection to the tech sector.

Example 2 – River Restoration: This class fosters an autonomous learning experience that highlights the complexity of river restoration. Lecturers act as experts to be consulted.

Example 3 – NADEL Interdisciplinary MAS project: This course works closely with external organisations who provide a challenge. This gives students a strong motivation to work hard as they have a public presentation to the organisations at the end.

Course information	**Module title:** Entrepreneurship **Lecturer responsible for the project:** Prof. Bart Clarysse **Further involved person/s:** ▪ Business Coaches: 3 ▪ Teaching Assistants: 3-4 (incl. one responsible for coordination) **Department:** D-MTEC; Chair of Entrepreneurship **Credits:** 3 ECTS **Class size:** up to 120 students from Bachelor to PhD
Learning goals/objectives	After this course, students will be able to understand: ▪ How technologies develop from science to commercial products

	▪ What kind of entrepreneurial opportunities emerge from this cycle ▪ How assumptions are tested in the market and evolve into business plans ▪ What the importance of founding teams is and how they are fit together ▪ How to raise money from various sources ▪ How to develop a business case ▪ How to negotiate and structure a funding deal *Transferable competencies (selected):* problem-solving, cooperation and teamwork, project management, customer orientation, creative thinking
Real-world or practice relevance/context	*Driving question:* How can we develop a business idea into a viable business plan and pitch it to an expert jury? *Practice context:* During the course, teams will create a business plan. In 2024, the best plan (voted by a panel of external experts) will go to compete in the Innova Europe Business Plan competition.
Process and student agency	*Length/format of module:* ▪ 14 weeks ▪ 6 lecture inputs ▪ 5 coaching sessions (timed to be after the lectures) ▪ Pitching to external jury members *Student agency in the project:* ▪ Students can bring their own business idea or select an idea to join via a marketplace where other student ideas have been shared. ▪ All students go through a self-assessment process designed to tell them what sort of team member they are, using tools like Kolb's Learning Style Questionnaire. ▪ Based on this, they form teams of 5-6 people who have complementary team styles.
Guidance and coaching	▪ Coaching sessions offer groups feedback and direction based on their deliverables.
Review and assessment	▪ 5 project deliverables that encourage students to form a team, identify a problem and solution, explore markets and prototype their ideas (10%) ▪ Public pitch – Dragon's Den style (20%) ▪ Business plan (20%) ▪ End-of-semester exam (50%)
Reflection and evaluation	▪ Feedback on assignments and grade can be requested at any time

Table 2: Entrepreneurship Course.

Course information	**Module title:** River Restoration **Lecturer responsible for the project: Dr. Volker Weitbrecht** **Further involved person/s:** ▪ Lecturers/experts: 4 ▪ Admin support and team management: 4 **Department:** D-BAUG; Laboratory of Hydraulics, Hydrology and Glaciology (VAW) **Credits:** 3 ECTS **Class size:** Max. 40 students, MSc level
Learning goals/objectives	After this course, students will be able to: ▪ Describe the most important relations in river morphodynamics[8] and their impact on the ecosystem of riverscapes ▪ Elaborate solutions within river restoration, dealing with the different societal expectations towards riverscapes. ▪ Deal with personal, social and technical obstacles in the planning of a river restoration project. *Transferable competences (selected):* analytical competencies, project management, creative thinking, cooperation and teamwork, communication
Real-world or practice relevance/context	*Driving question:* How can we revitalise a river section and restore near natural processes to increase habitat quality and biodiversity? *Practice context:* In 2023 and 2024 the case study area is a 1.7km stretch of the Töss River, Canton Zürich.
Process and student agency	*Length/format of module:* ▪ Expert inputs from lecturers ▪ A role play exercise ▪ Self-guided fieldtrip to the study site and field trip to a completed restoration project ▪ Coaching sessions with lecturers (3 in total) ▪ Presentation session in a market-place format *Student agency in the project:* ▪ Students can select from several focus topics they would like to work on. ▪ The project work is very self-guided: students have to discuss and agree which possible topics to work on, which questions to answer and what the report will contain. They are supported by a grading rubric and coaching to ensure that their decisions will meet the expectations of the lecturers (e.g. to avoid missing out a vital section due to lack of knowledge).
Guidance and coaching	▪ Coaching sessions from lecturers for each of the focus topics. ▪ Optional coaching and feedback sessions from Teaching Assistants are regularly offered during the semester during regular office hour slots. ▪ Optional expert opinions from lecturers can also be requested.

[8] The process by which channel form affects the dynamics of water movement and hence the evolution of channel form

Review and assessment	▪ Project report (50%) ▪ Project presentation in the form of an elaborated situation map (not Powerpoint) (25%) ▪ Peer review of another group's report (25%) ▪ Bonus grade for active participation (+0.25 on final grade)
Reflection and evaluation	▪ Self-reflections on the role-play exercise and field trips in the form of a voice note ▪ Feedback on the class is solicited via an online collaborative tool

Table 3: River Restoration.

Course information	**Module title:** ETH NADEL MAS Interdisciplinary Sustainable Development Challenge **Lecturers responsible for the project:** Jasmine Neve **Further involved person/s:** 4 lecturers/coaches **Department:** D-GESS; NADEL Centre for Development and Cooperation **Credits:** 4 ECTS **Class size:** 24 students, continuing education level (Masters in Advanced Science, MAS)
Learning goals/objectives	After this course, students will be able to: ▪ Systematically analyse specific sustainable development challenges, & design possible solutions, taking into account scientific evidence, user perspectives; and the complexity of the tackled sustainable development challenge (including the social, environmental, economic system in which it occurs). ▪ Apply tools to prompt creativity, innovation and complex problem solving, including design thinking, systems thinking. ▪ Build collaborative relationships with others from diverse disciplines and exchange feedback and ideas constructively. *Transferable competencies (selected):* problem solving, cooperation and teamwork, communication, creative thinking
Real-world or practice relevance/context	*Driving question:* How can we address sustainable development challenges that are complex, interdisciplinary and intercultural in nature? *Practice context:* 8 international cooperation partner organisations present 8 sustainable development challenges they are facing.
Process and student agency	*Length/format of module:* ▪ 14 weeks (1 semester) ▪ 5 classroom sessions with lectures and group work ▪ 1 pitching event with partner organisations ▪ Approximately 20 hours group work outside the classroom ▪ Approximately 35 hours of individual work (reading, research, writing) *Student agency in the project:* ▪ Students form interdisciplinary groups based on their industry background

	▪ Student groups can select the challenge they want to work on. Challenges are provided by the partner organisations
Guidance and coaching	▪ All groups have a supervisor from NADEL who provides feedback at two interim deadlines during the semester on the draft problem analysis and the proposed solutions. ▪ Peer feedback is encouraged throughout. ▪ Three exchanges with the project partners are organised during the project.
Review and assessment	▪ Concept note (including academic literature review) (65%) ▪ Pitch (20%) ▪ Active participation (15%)
Reflection and evaluation	▪ Two reflection rounds were organised to help students address issues that they encountered.

Table 4: NADEL Interdisciplinary MAS Challenge.

Conclusions and implications for higher education

This paper has outlined the historical development of project-based education – both broadly and within ETH Zurich. Rooted in long-standing traditions of higher education, PBE can be framed as a highly relevant approach for university teaching, helping connect the three missions of a university. Based on the history and examples presented here, several key implications for delivering project-based education within ETH Zurich can be identified. These implications will also be relevant to other higher education institutions when they foster PBE.

First, the potential for PBE to foster transferable competencies is an important aspect to consider when thinking about curriculum design. If students in a curriculum have several PBE courses at different points, there may be specific competencies that are fostered across several courses, for example project-management or collaboration. At a curriculum-level it could be helpful to coordinate how these competencies are covered in different courses, to avoid repetition of basic information or methods - a 'stacking' of competence-based content. Similarly, PBE courses often benefit from the content taught earlier on in a curriculum – students may already know methods or knowledge that they can use for a project. However, when the learning transfer is not sufficiently clear, students may not realise that they can use that prior knowledge – a missed opportunity, requiring more content-heavy input from the PBE lecturer that may be repetitive for some students. Close alignment by lecturers of content-focused and project-focused courses across a curriculum can strengthen the overall learning experience and have been documented elsewhere (e.g. Habbal et al., 2024).

Secondly, designing PBE courses opens up opportunities for building up interdisciplinarity in teaching. Real-world contexts, problems and challenges often need students to delve into many different aspects of a topic, encouraging them to connect knowledge from different areas. When classes have diverse student groups this can explicitly encourage interdisciplinary exchange – for example, the NADEL course outlined above (example 3) asks students to build teams of peers from different sectors for the project, to strengthen creative thinking and solution finding. In complex contexts, or where interdisciplinarity is an explicit goal of a course, students may need to put more time into learning new methods, gathering background knowledge or incorporating diverse perspectives compared to a more subject-specific course, and projects can benefit from larger courses with more credit points to provide sufficient time for exploration.

Thirdly, and given the above points, it seems likely that implementing PBE will foster communication and exchange between lecturers, and ultimately that 'communities of practice' (Wenger-Trayner et al., 2022) – a group of people informally bound together by shared expertise and passion for a joint enterprise – will develop within and across departments to share their experiences, strategies and classroom techniques without necessarily teaching together. Indeed, Oliveira discusses the essential role of community in ensuring that efforts to create PBE curricula are maintained as staff members leave and HE strategies change (Oliveira, 2023), and ETH Zurich already has communities of practice within some departments (e.g. Bondar et al., 2024).

Fourthly, the topic of classroom or teaching spaces is also important. PBE often requires multiple classroom set ups – for example plenary lectures, poster sessions, group spaces, design studios and more. The examples in this paper range from lectures to field trips, coaching sessions, idea 'market places', and pitching events. As PBE becomes more important within an institution, the teaching spaces needed will change from traditional raked lecture theatres to more flexible, open spaces capable of hosting diverse classroom formats. If PBE work involves the creation of physical objects or prototypes, then there may be additional need for workshops and lab spaces that are used in new ways to classic teaching labs where multiple classes are accommodated on a regular basis. PBE is therefore likely to require greater efficiency in sharing and reuse of tools, resources and spaces across departments. This is an important consideration at a time when the scarcity of resources is a problem within institutions as well as in wider society.

Fifthly, PBE challenges traditional perceptions of university teaching. In primary and secondary education, the shift has been described as 'from the sage on the stage to the guide on the side' (Larmer et al., 2015). Engaging with and learning from the expertise and deep knowledge of university lecturers is one of the great opportunities for students in higher education. While PBE emphasizes student agency and increased responsibility, it does not mean that the profound knowledge base of university lecturers and researchers are no longer needed. On the contrary, their deep knowledge of their subject, the methods used to advance it, and its contribution to the wider world and its problems remains essential. PBE is different from the traditional lecture-based approach that has long dominated higher education, but builds upon it. The examples in this paper, each involving 3-4 additional academics or professionals, suggest that even in small classes, multiple experts are essential for a comprehensive teaching experience. Given their changing role, lecturers will need to have and use their own competencies in coaching, team-management and project planning to guide, advise and support students in PBE formats.

Finally, at institutions with large student cohorts (like ETH Zurich where classes can have 400+ students), attaining good student to lecturer ratios will require the appointment of teaching assistants able to support project-based courses. ETH Zurich has long offered training in coaching skills for teaching but is now developing a more structured approach to train teaching assistants in coaching skills, to enable them to support and co-deliver PBE courses as 'student coaches'.

Universities are complex places, subject to contradictory missions (Berghaeuser & Hoelscher, 2020; Etzkowitz & Leydesdorff, 2000). Teaching, one of the three core missions of universities, is the connection point between the other two (doing research and adding value to society). The way teaching is designed and delivered is critical if current students and future members of society are to acquire the various competencies (both subject-specific as well as transferable) that they will need to navigate a rapidly changing world and its increasingly knowledge-based economy (Collini, 2012; Harvey, 2000; La Cara, 2023a). Project-based education provides a useful frame for discussions about what students need to learn and how this can be taught. The adoption of PBE will encourage learning environments to align with the real-world context most graduates will end up in. PBE will bring changes in how curricula are designed and will support lecturers and TAs to reimagine their roles to meet the changing world. These changes will help the higher education sector stay relevant.

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‘Everything I love about physics’ in a project-based undergrad lab course

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Abstract

We report on the development and implementation of P+, a novel project-based physics lab course. In this inquiry-based format, students choose their own topics, design and build the experimental setups, and conduct their own experiments. We discuss the pedagogical rationale behind P+, its implementation within the existing lab course format, and the challenges and successes encountered in the first two semesters of its conduction. We assess the skill development via a student survey, tracking their self-perceived skill levels associated with a set of learning goals. We find that all learning objectives are achieved in the new format at least to the same extent as in the standard laboratory course. Particularly positive effects are observed in the categories ‘designing an experiment’ and ‘scientific communication’. In addition, students benefit from increased collaboration, a structured approach to project development, and the opportunity to explore their interests, which leads to exceptionally high motivation, a key factor for efficient learning.

Introduction

The primary goals of undergraduate physics laboratory courses at most universities are to equip students with the basic skills needed to conduct experiments, to familiarize them with laboratory equipment and procedures, and to strengthen their understanding of physics concepts taught in lectures (see e.g. Sokołowska & Michelini, 2018, chapter 5). While phenomenological experiments have long been the gold standard for introductory physics lab courses, there has been a growing emphasis in recent years on open-inquiry and project-based approaches. In 2022, in the aftermath of the COVID-19 pandemic, we set out to improve the physics laboratory curriculum at ETH Zurich through the development of a **P**roject-based **P**hysics **L**ab for **U**ndergraduate **S**tudents, P+ for short. The pandemic had necessitated a switch to remote lab classes, with students conducting self-built experiments at home. This experience revealed that certain skills were more effectively developed in this remote format compared to traditional laboratory settings due to the stronger involvement of the students in setting up an experiment. Based on this insight, motivated by the excitement about the Physics-At-Home experiments (Walther, 2022), and inspired by the success of the Projektlabor at the TU Berlin (Merli et al., 2020), in the spring semester of 2023 we conducted a pilot phase for an open-inquiry project-based lab class in which students choose the topics, develop and build the setups and carry our their own experiments. With funding from the Innovedum initiative at ETH Zurich in 2024 (ETH Zurich, 2024), we were able to expand and consolidate P+ as a sustainable alternative to the standard physics lab course. The new course found great resonance among the students as illustrated by the student testimony cited in the title of this paper. We report on the development and implementation of the novel format, describe the course structure and analyze the self-reported skill development of the P+ students in comparison to their colleagues in the traditional lab course.

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Implementation of P+

Learning goals

Inspired by our experiences with the 'at-home' experiments during the COVID-19 pandemic (Walther, 2022), we sought to implement a similar approach in our second-year undergraduate physics lab course at ETH Zurich. When embarking on the task of improving an existing course, the suitability of current and new course for teaching the desired learning objectives must also be quantified. We wanted to find out whether a project-based approach is as suitable or maybe even more efficient for teaching experimental skills. However, our main focus was on skills that cannot be taught, or only to a limited extent, in a traditional laboratory course. We defined a set of learning goals, leaning on the framework established by Zwickl et al. (2013). In this concept, the individual learning goals, e.g. 'oral presentation of scientific results' or 'ability to describe data in a compelling way', are sorted into four main categories - which would be 'scientific communication' in case of the examples given. A sketch is shown in Figure 1, and a list of all learning goals and their associated skills is provided in the appendix. Similar approaches to shift from guided-inquiry lab courses towards more open-inquiry experiments have been used at other universities, and an instructive description of such a transformation process can be found in Sokołowska & Michelini, 2018, chapter 8.

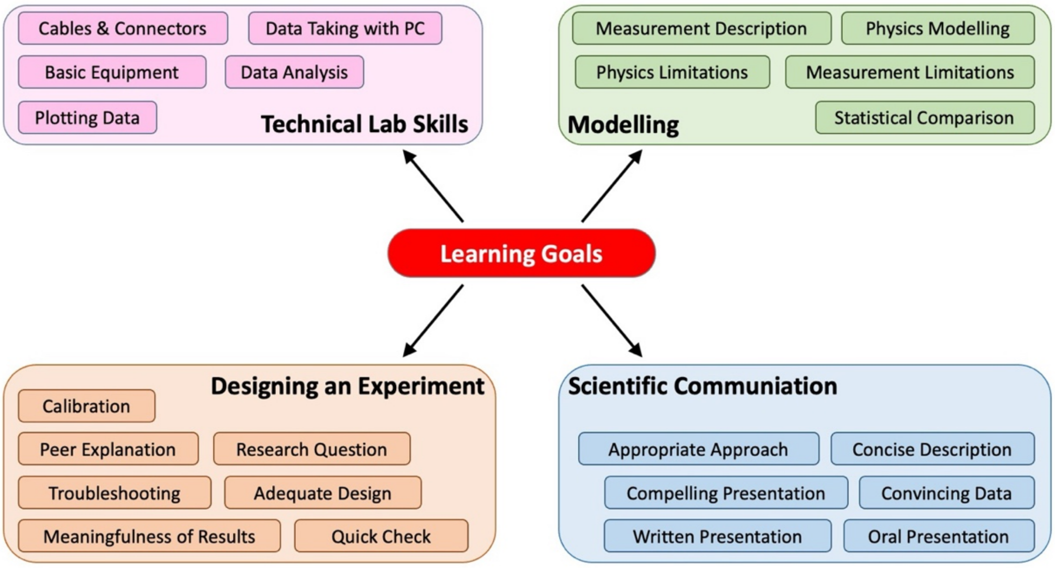

Figure 1: Overview of the learning goals and associated skills, sorted into four categories, leaning on the concept of Zwickl et al., 2013. Learning goals and the associated questions asked are listed in the appendix in Table A1.

It is clear that many of these learning goals are not addressed in the context of a traditional lab course. At ETH, the standard physics lab class is conducted in groups of two students during one half-day every week. The students work on readily available setups and perform a predefined sequence of experimental tasks. A teaching assistant who supervises the same experiment throughout the semester supports them if needed and takes care of correcting the reports. This means that students meet different teaching assistants each week, which increases the variety of inputs but at the same time does not allow for monitoring their progress over the semester. Several learning goals, such as designing and modeling, are not addressed when using given setups. Other skills, such as troubleshooting a setup, can only be trained within traditional courses if artificial hurdles are introduced. However, deliberately introduced bugs and problems in setups cannot provide an authentic learning experience. Finally, such transferable skills as planning and group collaboration can only be learnt while working on a full project, which is not possible in traditional lab courses. Therefore, we needed to change the existing organization of the lab courses quite fundamentally for P+, as described in the next section. This detailed and in part more technical description may also serve as a blueprint for similar endeavors.

Organizational structure of P+

At ETH, physics students visit the physics lab course in the second and third year of their Bachelor studies. After having absolved the ‘Basisjahr’, they first participate in the beginner’s lab classes called ‘P1’ and ‘P2’, followed by the advanced lab classes ‘P3’ and ‘P4’ (or an equivalent course, such as a semester project in a research group). The goal of P1 and P2 is to equip the students with the fundamentals of lab work, whereas P3 and P4 focus more on advanced physics and complex experimental setups. We introduced the project-based P+ with currently 36 places as an elective alternative to P2, i.e., after the students have completed their first semester of lab classes.

The structure for the standard lab course, as described briefly in the previous section, is unsuited for open-inquiry experiments. Because the students come with their own experimental ideas and need to think about and build a setup for their needs, every single experiment requires much more time for development. Execution of the experiment, the central part of traditional lab courses, is only the final step in P+. The variety and complexity of tasks until the experiment can be performed requires larger groups. In the P+, students work in groups of 6 and are accompanied by the same teaching assistants throughout the semester. In addition, the groups are supported by an advanced supervisor (the lecturer or an additional, advanced ‘head TA’, as explained in the next section). The very consistent support allows for close monitoring and steering of the individual’s and group's progress. It is also necessary for balancing the much greater freedom of the students, including the substantial risk of failure of a self-created experiment.

In the first week of the semester, a kick-off meeting between the group TAs and their students is scheduled. This helps strengthen the cohesion within the group and allows the students to get a feeling for the unfamiliar modes of working in a team and being responsible for their own goals. At this stage, the group also decides on the topics of the six experiments which they want to carry out in the coming months. The head TA or lecturer only intervens if necessary, e.g. to promote a more balanced selection of physics topics, or experimental and data analysis techniques.

From this point on, a clear organizational framework for the experiments is given, as shown in Figure 2, following a two-week cycle which is repeated six times throughout the semester. In the following, a sample schedule of such a two-week cycle is discussed.

Planning phase (week n):

In the first week of each cycle, the focus is on planning the experiment. Although students can organize themselves quite freely, there are two mandatory one-hour sessions. It is advisable not to schedule these on consecutive days, as a lot of researching, discussion, and plan refining is required between these sessions.

In ‘Tutorium 1’ (see Figure 2), students meet with the group TA to develop a first draft of their chosen experiment and its setup. It is important that students are guided at this early stage to structure their work well by identifying several goals and milestones of their experiment. Breaking down the overall goal into smaller steps has proven to be very important, as students tend to set their initial goal too high to be achievable in a realistic time frame. Another challenge the students face lies in the understanding of the physics underlying their experiment. This includes the typical application of a fundamental concept and equation to a concrete problem. However, they must also ensure all group members grasp the theoretical background. In the context of P+, they have the chance to have a guided (by the TA) but peer-centered discussion about physics.

The second mandatory preparation session, ‘Tutorium 2’, is dedicated to finalizing both the experimental plan and the details of the setup that needs to be built. The students discuss the specific measurements they will take, which results they expect, and how they will assemble the experiment in detail. By the start of the second session, students have the task of creating a list of the required equipment and materials. This allows TAs, the lecturer and technical staff to review their plan at this stage, ask clarifying questions and possibly suggest improvements to the setup. If the list of the desired material and equipment is in line with both the financial and time budget (of technical staff as well as students), the group will receive 'green light' and the equipment is organized, built (if possible, by the students), or purchased.

Execution phase (week n+1):

The second week is dedicated to executing the experiment. The third time slot (2.1, see Figure 2) is kept free of mandatory meetings, giving students time to work independently on their projects. Most groups use this slot to start building their setup, test some prototypes or perform preliminary measurements.

During the fourth time slot, the experiments are finally carried out. At the beginning of this half-day, all students participate in the 'Vorsprache', a set of short presentations that serve as an entry ticket to perform the experiment. Typically, three groups are scheduled together and present their final experimental plan to each other, explain the setup and provide a brief theoretical background. While the groups prepare the presentations together, typically using a whiteboard, only two randomly selected group members give the presentation. Most questions are asked by the other student groups but also the head TA or lecturer may ask questions and ultimately decides whether the students are prepared enough to be admitted to the experiment. Besides serving as quality assessment, the presentations also train students in scientific communication, a fundamental skill for scientists.

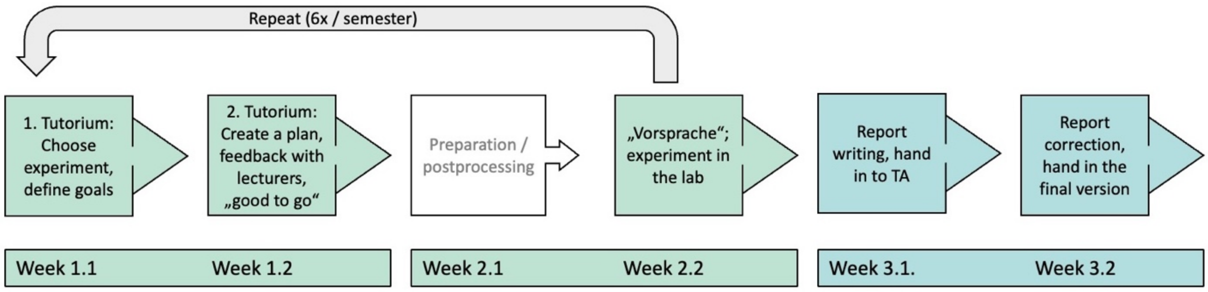

Figure 2: Two-week cycle of a P+ experiment, repeating 6 times per semester. Ideally, the slots with mandatory meetings are not on consecutive days, such that the students can progress on their tasks by themselves.

Once the 'Vorsprache' is successfully mastered, the students start to experiment. The official agreement is that they should carry out their experiment within the next four hours, reaching at least a certain step of the experimental plan, which is agreed upon in the planning phase. This will suffice for passing the experiment. In many cases, however, it turned out that the students and their group TAs were motivated to push further and stayed much longer. From the lecturer's side it is important to stress that staying (significantly) longer is not expected and promoted. But as a student explained, 'we could have gone home after reaching the first milestone, but we just really, really wanted to reach the next level'.

Upon completion of the experiment, a scientific report has to be written within one week. In each cycle, two students are assigned to be main responsible authors, while the other group members support them. The report is submitted to the group TA and later to the head TA for corrections and iterated in a peer-review manner until its acceptance.

Students supervising students with an advanced teaching assistant supporting in the background

The P+ pilot project in 2023 had already received a very positive resonance among the students and had been overbooked by a factor of two (18 student slots for 36 subscribed students). To expand the capacities, we adapted our supervision structure by including another supervision layer. The pilot phase of P+ had highlighted the importance of effective teaching assistant (TA) supervision for student learning in this project-based approach. For the first round of P+, two of the authors and another experienced and extremely motivated TA served as group TAs. The initial supervision structure is depicted in Figure 3a).

It was clear for us that especially the role of the lecturer was not scalable, who was heavily involved in checking the feasibility of the experiment per se, as well as the experimental setup. In addition, the tasks of providing technical support and executing quality control (this includes the quality of the research questions, sufficient preparation of the students, the quality of the report, but also the safety of the experimental setup) consumed a significant amount of time. The teaching assistants, on the other hand, were well occupied with guiding the students through the development process of their experiment, supporting them in theoretical and experimental difficulties, and dealing with group dynamics. While the teaching assistants, who were quite experienced themselves, could have taken over a large part of the quality control, they did not have time in this supervisory structure, and it would also have led to role conflicts, since they would then have been both the 'best friend' and the controlling authority of the group.

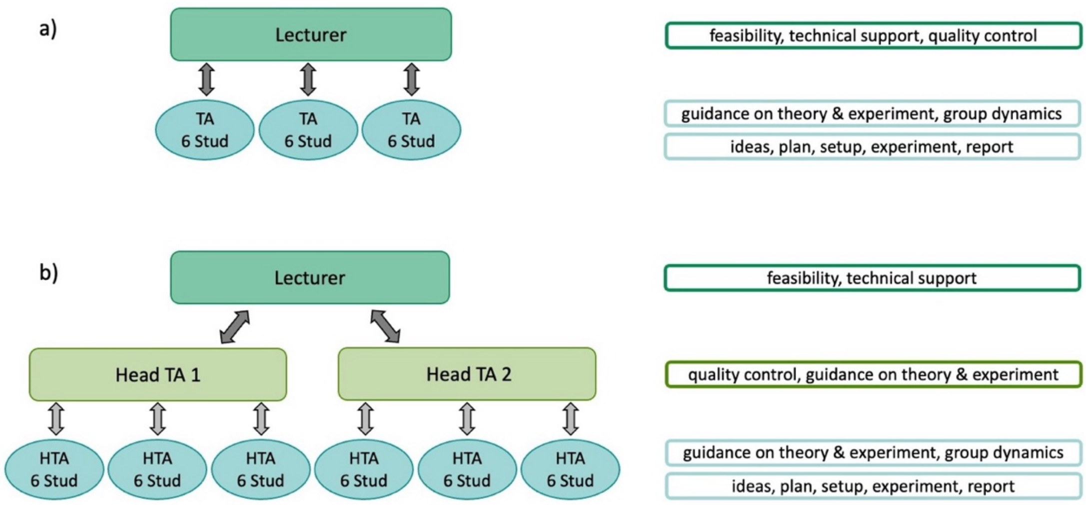

Figure 3: Structure of the supervision a) in the pilot year 2023 and b) in 2024, where budget was available to hire student teaching assistants (HTAs) and use regular TAs as additional supervision layer. The main tasks and responsibilities are listed on the right-hand side.

In order to upscale the P+ capacity and make the concept more sustainable in terms of teaching hours and preparation time, for the second round we implemented an additional layer of supervision by adding the role of head TAs and introducing student teaching assistants (HTAs) as group TAs. This significantly reduced the lecturer's workload, because the quality control as well as part of the feasibility considerations could now be delegated to the head TAs. This structure is sketched in Figure 3b). Every head TA is responsible for 3 groups, each group is accompanied by one HTA. The head TAs, having a broader experience and knowledge in experimental physics, can advise the groups already in an early stage regarding experiment construction, and assist the lecturer by sorting out unfeasible experiment ideas at an early stage. The group (H)TAs in turn are close to their respective groups and can contribute well to a constructive and supportive group atmosphere.

With the introduction of HTAs as group TAs, the capacity of P+ could be doubled from 2023 to 2024: 36 instead of 18 students in P+, corresponding to 18 students per head TA. We could directly recruit the HTAs from the veterans of the P+ pilot and finance their salary by an Innovedum grant (ETH Zurich, 2024), which also gave us the opportunity to purchase further equipment and tools, such as a 3D printer, for the P+ students. In the perception of the students, the HTAs, due to their recent undergraduate experience, felt more approachable, which encouraged the students to ask questions more readily. The HTAs were found to be extremely motivated, spirited, and involved and in many cases served as an additional driver for their groups. This factor, on the other hand, possibly influenced the students' invested time into P+, which increased from 2023 to 2024, as further discussed below.

Results from the students' survey

Quantifying the effectiveness of P+ to achieve the set learning goals, even in relation to the traditional P2 laboratory course, presents several challenges. First, at ETH Zurich, neither P+ nor P2 have a formal performance assessment (e.g., exams or grading of the reports) which could be compared. Second, the immense variety of the projects within P+ makes a straight-forward comparison of student skill acquisition nearly impossible. How, for example, can one objectively compare the development of a cloud chamber with particle trail analysis using AI algorithms against the construction of a Stirling engine? Finally, the small group of students in P+ during the past two academic years makes any statistically significant quantifications difficult, a fact that should be kept in mind when considering our results.

Nevertheless, attempting to evaluate whether our changes were effective, we carried out a student survey. The questionnaire included a self-assessment of 23 distinct skills corresponding to the learning goals defined in Figure 1 and a second part with a general evaluation of P+. The survey was completed twice by the students; once before and once after the semester. A unique anonymous six-digit identifier allowed comparing pre- and post-course feedback.

As in both years the demand for P+ was a factor of two higher than the capacity, we could include all students who applied for P+ into the survey, and use those students as a test group who didn't get a spot in P+ and thus carried out the standard course P2. Given that the students all had applied for P+, we assumed that there would initially be no significant difference between them. Comparing students who are interested in participating in a novel and project-based lab course with those who avoid it, might, however, produce an inherent bias. The exclusion of all students who did not apply for P+ contributed to an overall small number of returned questionnaires: In total, pair-wise analysis could be performed for 11 students in P2 and 35 students in P+.

In the first part of the questionnaire, the students were asked to rate their own skill levels in the categories discussed above on a scale from 0 to 10, with 0 indicating 'no skill' or 'no experience', and 10 indicating 'expert skill' or 'expert experience'. Figure 4 shows spider diagrams of the self-assessed skill levels in two main categories, 'technical lab skills' and 'designing an experiment'. In Figure 4a), the 5 skills connected to 'technical lab skills' are displayed. The shaded grey area in the center represents the skill levels before they visited the physics lab (called 'pre-lab'). The solid blue line represents the self-assessed skill level of students after completing P2, and the solid orange line of those completing P+. The similar curves indicate that in the category 'technical lab skills', the students perceive an increase of their technical lab skills in either lab course format by an almost equal amount.

As a general finding, for every learning goal we found that within the framework of P+, at least about the same perceived skill levels were reached as compared to the traditional lab course (Figure 4a represents the 'worst result' for P+ in that regard). In several categories, P+ students rated their skills after the semester much higher than the P2 test group. One example for such a much higher rated category is given in Figure 4b): In 'designing an experiment', P+ students felt much more competent.

In Figure 5, we show the average perceived increase in skill level for all 23 learning goals. This value is calculated as the difference between the rated skill level after and before visiting P+/P2 for every student individually, and then averaged over all P+ and P2 students, respectively. Here we see again that the P+ students rate the increase of their own skill level at least as high as the P2 students do, while in many categories the perceived competencies have improved much more within the new format.

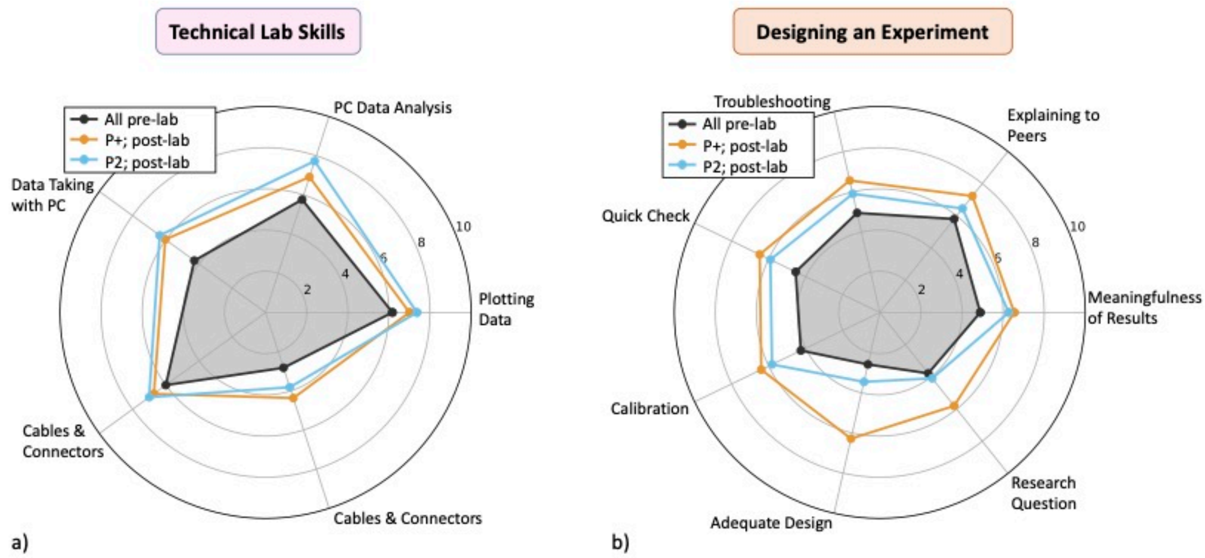

Figure 4: Spider diagrams of the perceived increase in competence by the students, where the skill levels before ('pre-lab') and after ('post-lab') completing the more standard P2 and the novel course, P+, respectively, are compared. Shown are the averaged data for the 5 skills from a) the main category 'technical lab skills' and b) for the 7 skills of the category 'designing an experiment'.

In the second part of our questionnaire, we posed more general questions about their experience with the P+. The answers overall were very positive and enthusiastic. When we asked: 'on a scale from 1 (=never) to 10 (=by any means), would you do P+ again?', twelve out of twenty students answered with a 9 or 10, and only four students answered with a 4 or 5, the lowest marks given. Another very strong example for the good reception of the P+ was the inquiry whether they could imagine becoming an HTA for the P+ in the coming semesters. Fourteen out of twenty answered with 'yes', while three were undecided and four said 'no'. The most frequent answer to our open question about what the P+ had taught them in addition to the above asked skills was 'team management', followed by related competencies, such as conflict, time or resources management.

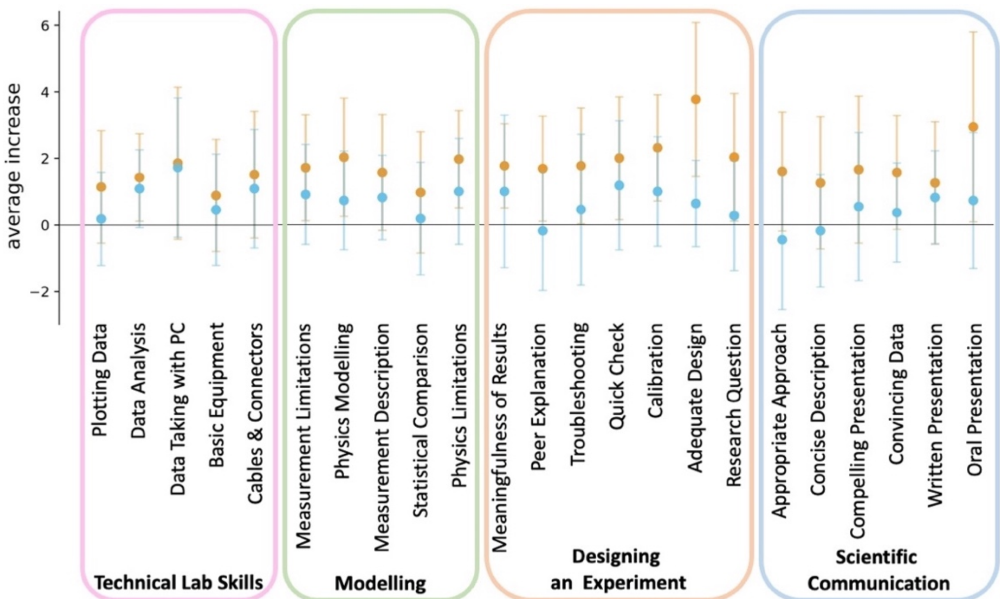

Figure 5: The relative increase for all 23 skills (corresponding to the learning goals as defined in Figure 1 is shown as reported by the students in P2 (blue) and P+ (orange).

Last but not least, we asked the students how many hours they invested in the physics lab course. Students receive 6 ECTS credits for P2 or P+, which corresponds to a nominal workload of 180 hours. In our experience, the P2 takes about 100 hours. In the pilot phase of P+ in 2023, students reported an average time investment of 120 hours, with 2 students working 180 or more hours, and 5 students working 100 or less hours. In the consolidation phase in 2024, the reported average increased to 151 hours. The extensive time spent for P+ was one of the main points of criticism coming from the students. Other students said that the experiments felt ‘a bit rushed’. Thus, in future development of P+ we will try to balance the allotted time for the experiments better, as further discussed below.

We want to conclude this section with two student testimonies that stand for all the valuable feedback we received that motivates us to further invest in and develop P+ in the years to come:

- ‘I learned how to discuss experiment ideas, distribute tasks and discharge unrealistic ideas. I communicated a lot with my HTA but also with [the lecturer and head TAs]. It was by far the most contact I ever had with teaching people at ETH. In general, the experience was incredibly diverse, the learning process was much more multilayered than in P1 and to me the work felt like the most meaningful for my formation during my studies at ETH so far.’
- ‘It will cost you a lot of time. But P+ is everything what I love about Physics, and to be able to experience it while in the second year of physics is phenomenal.’

Discussion

The positive student feedback and the improved perceived skill levels were a very satisfying outcome for us, but the question is valid: Do these data also reflect the students’ learning? While acknowledging the limitations of self-assessed data, research (Deslauriers et al., 2019) has shown that self-assessed skill levels can be a reliable and instructive measure for the efficiency and efficacy of a new course. The study even indicates that perceived competencies tend to be rated lower by students taking part in an active learning format as compared to traditional formats, while they ultimately score better in formal assessments.

In our survey, the overall increase of perceived skill levels is observable and substantial. Especially in ‘scientific communication’ and ‘designing an experiment’ it appears that the learning goals can be achieved better in the project-based lab format. It is also easy to understand that some learning goals are only addressed in one course format and some are almost mutually exclusive. For example, teaching students a lot of experiment design and letting them invent setups by themselves will obviously not improve the skills in categories such as ‘knowing cables and connectors’ equally well as for a guided-inquiry classical lab experiment.

A defining characteristic of the P+ students was their exceptional motivation. They show great motivation to understand complex physics phenomena and often exceed expectations in terms of time commitment and effort. A student's response to Nobel Laureate Carl Wieman during a visit of P+ in May 2024 serves as a striking example of this strong motivation: When asked about their higher time investment compared to their colleagues in the traditional P2 course, she replied: ‘Yes, but we also learn much more than they [students in P2]! We have here the opportunity to do real physics, and of course we could stop after reaching our first milestone, but we want to reach the next milestone as well!’.

As underlined by Self-Determination Theory (SDT) (Ryan & Deci, 2020), intrinsic motivation is a cornerstone of effective learning. We firmly believe that the autonomy given to the students in the P+ fosters their motivation and thus a positive learning environment. Research in the context of SDT showed that intrinsic motivation also leads to greater identification of undergrad students with being scientists (Skinner et al., 2017). This identification is known to be key for the success of students, with particular impact on students from underrepresented groups, namely women in STEM, first-generation university students, and other minorities. In P+, it is further fostered by the strong sense of belonging to their group and the experience of competence that clearly emerges from our survey. For us, these facets of P+ are of utmost importance.

Taking into account the students' criticism and suggestions for improvement, we plan to further optimize time management within P+, balancing the time invested by the students and the variety of topics, while at the same time maintaining the students' autonomy, as is is directly linked to their motivation.

One possible solution that takes both the ‘rushed feeling’ and the high load into account is to reduce the number of experiments during a semester and increase the allocated time for them. However, this could have the disadvantage of limiting the range of topics covered too much. Further, six experiments have the added benefit that each student can select a topic. In principle, by introducing experimental milestones, the students already have the possibility to complete their experiments within a reasonable time frame, and we recognize the importance of student motivation and appreciate their desire to ‘push through’ challenging projects. For us, the rewarding experience of leaving the laboratory tired but satisfied due to a successful experimental result is a beloved part of being an experimental scientist. But staying longer in the lab may not be fully by choice, it is possible that some students feel peer pressure. We will alert the group TAs and the supervising TAs to these possible dynamics and ask for clear communication when the ‘sufficient’ level of the experiment has been reached. Further, to avoid the frustration of failure, each group can at their own request drop one of the planned experiments every semester in order to continue with the current experiment in the following cycle and optimize it. This also allows them to train optimization processes, and they can achieve satisfactory success in the end.

In addition, we will try a simple but hopefully effective measure to let students make better use of the allotted experiment time. We will introduce ‘Experiment Zero’ as a module at the beginning of the semester in which important experimental techniques and skills are taught. The groups are split up, each member visiting one of six stations that focus on a specific topic (e.g. ‘temperature and pressure measurements’ or ‘3D printing’). Afterwards, students return to their groups as experts in their topic. We hope that this activity will foster efficient teamwork within and collaboration between groups. It will certainly help to avoid time-consuming experimental challenges, which we have observed frequently.

Conclusion

With the introduction of P+, we have created a valuable alternative to the traditional physics lab course, from which a significant proportion of students benefit greatly. The P+ paves the transition from guided, structured projects to open, self-managed group work. The high level of student motivation, reflected for example in the student testimony cited in the title of this work, demonstrates their appreciation for this new lab course format. We have observed improvements in students' skills across various areas which are important for their future work as scientists in research groups.

While project-based open-inquiry group work may not be ideal for all students, the insights gained from the P+ experiments have convinced us to also introduce some of the concepts in the traditional lab course P2. For example, we plan to adapt the supervision structure to one teaching assistant staying with a group of students for the whole semester. Further, the number of written reports will be reduced while increasing the depth and quality of those that remain.
Finally, we would like to comment on the broader applicability of our layered supervision system leaning on HTAs. One extremely positive aspect of P+ emerging from many discussions is that the HTAs benefited significantly from their experiences as group supervisors. Many expressed that their own physics knowledge and experimental skills improved even more than when being P+ students. Recruiting highly motivated HTAs as an option to partially alleviate the increasing need for teaching assistants across ETH therefore appears to be a win-win-win-win situation: for the students, the student TAs, for us in our role as teachers, and for the mission to provide high-quality teaching in the face of steadily growing student numbers.

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The evaluation and publication of the survey was approved by the ETH ethics commission under approval EK-2023-N-326, and its successor was exempted (EK-2024-E-10)

Appendix

Technical Lab Skills	Plotting Data	How would you rate your skills in plotting data in-situ for a rough, first approximation of a result?
	Data Analysis	How experienced are you in performing computer-aided data analysis?
	Data Taking with PC	How experienced are you with computer-aided data taking?
	Basic Equipment	How confident do you feel with handling basic lab equipment such as calliper, multimeter, oscilloscope etc?
	Cables & Connectors	How familiar are you with different cable types and connectors (e.g. BNC, LEMO, coaxial cables, shielded cables, ...)
Modeling	Measurement Limitations	How do you rate your ability to determine and formulate the limits of a measurement model? I.e. can you explain where your setup has shortcomings and which parts of the physics is neglected/ignored?
	Physics Modeling	How well can you develop a predictive model to describe the physics you want to investigate?
	Measurement Description	How well can you model and desribe a measurement system? I.e. how experienced are you in predicting what an input quantity for a measurement device is (e.g. CCD-camera), what is its output, and what happens in the device?
	Statistical Comparison	How experienced are you with statistical comparison between data and theory/model? (i.e. data fitting, indication of goodness of fit etc.)
	Physics Limitations	How do you estimate your experience in articulating limits of a physics model? How experienced are you in arguing up to which point your physics model can describe a phenomenon correctly, and where its limitations are?
Designing an Experiment	Meaningfulness of Results	How experienced are you with judging the meaningfulness of your results? Can you perform a plausibility check instantaneoulsy?
	Peer Explanation	How well can you explain an average physics lab experiment to your colleagues? This includes the underlying physics, the setup, measurement devices, expected results and the interpretation of measured data.
	Troubleshooting	How do you rate your skills in troubleshooting a setup and finding mistakes when something does not work in the lab?
	Quick Check	How do you rate your skills in quickly checking a setup and verifying that all components work as they should? (compared to the quesiton above, this is usually done before the measurement is started)
	Calibration	How experienced are you with calibrating a setup?
	Adequate Design	How do you rate your skills in designing an experiment in a clever and efficient way, and how well can justify why this design is the most appropriate?
	Research Question	Every setup is designed based on a well-defined, testable research question. How well can you specify independent, dependent and control variables in a setup?

Scientific Communi-cation	Appropriate Approach	How do you rate your skills in defending a chosen approach to measure a quantity, when you have to compare it to other ways of measuring the same quantity?
	Concise Description	How do you rate your skills in describing an experimental setup in a concise, scientific way?
	Compelling Presentation	How do you rate your experience in presenting data in a compelling way, which also non-experts in this particular field find easy to interpret?
	Convincing Data	How experienced are you with reasoning why your data is convincing? This includes that you have to account for possible short comings of the setup, and why their influence is (hopefully) of minor importance.
	Written Presentation	How do you rate your skills in writing a scientific report presenting your ex-periment (theory, model, setup and data analysis)?
	Oral Presen-tation	How do you rate your skills in presenting and defending a setup and ob-tained results orally? This can be in front of peers (e.g. Vorsprache in P+), a teaching assistant, or any other knowledgeable but non-expert audience.

Table A1: List of questions asked in the questionnaire.

Assessing students' motivation, learning, and skill transferability in a real-world project: Insights from the ETH Assistive Technology Challenge

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Abstract

Challenge-based learning addresses socially relevant real-world challenges and requires students to work closely together with stakeholders in a highly engaging and interdisciplinary manner. The newly established ‘Assistive Technology Challenge’ course at ETH Zurich promotes challenge-based learning by exposing Health Sciences and Technology students to diverse disciplines and skills of importance in the field of assistive technology. During the course, the students without an engineering background work together with a person with a physical disability to (co-)develop a personal technical solution for an individual challenge that the person encounters in their own daily life or during leisure activities. This work describes the course format, student assessment, and outcomes of the first edition of the course executed during the spring semester 2024. Further, it describes the outcomes of an online survey collecting students' feedback on the course and investigates how the chosen course format affected the learned competencies and students' motivation. Results show that the course format enabled students to achieve a successful project outcome, promoted high student motivation, and strengthened their competencies in areas expected to be relevant for their future careers.

Introduction

Project-based learning has been shown to result in significant improvements in learning outcomes compared to conventional teaching approaches (Moreno-Ruiz et al., 2019) and to be beneficial for acquiring transferrable competencies such as, e.g., teamwork, communication, problem-solving, and self-directed learning (Sukacké et al., 2022). To maximize students' engagement and learning of such competencies, implementing project-based courses tackling projects in real-world conditions is expected to be highly beneficial (Li et al., 2019). Challenge-based learning even goes one step further by addressing actual real-world challenges. By working collaboratively with relevant stakeholders (e.g., from industry or from the public), students identify, analyze, and design solutions for socially relevant problems in a highly engaging and interdisciplinary manner (Sukacké et al., 2022).

The user-centered design (UCD) process (Abras et al., 2004; International Organization for Standardization, 2019; Norman & Draper, 1986) is a powerful framework for implementing challenge-based learning. An area where UCD is crucial is the development of assistive technologies (AT). AT aim to increase the functional capabilities of people with disabilities, thus increasing their independence and enabling them to engage in various daily and social activities. This is especially important as acceptance of many AT is low, mainly because they do not satisfy the users' needs and show low usability in daily life (Sugawara et al., 2018). Further, a single design is often not suitable for all users of AT. Hence, solutions need to be tailored to individual users (Kintsch & Depaula, 2002) and their individual context of use (i.e., personal needs, preferences, and usage environment). Thus, involving target users throughout the development process is crucial (Shah & Robinson, 2007). However, users are often only

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involved at the very end of the development phase when incorporating their feedback is resource-intensive or no longer possible. As such, the benefits of applying UCD of AT in an educational context are twofold: On the one hand, there is a strong need to educate future AT developers already early in their career about the benefits of UCD to maximize the usability and, thereby, acceptance of the developed technologies. On the other hand, it offers an ideal use case for challenge-based learning, as students do not only work on real problems with high social relevance but are also required to extensively exchange and work together with the target users in order to (co-)develop meaningful solutions.

The ‘Assistive Technology Challenge’, offered for the first time in the spring semester of 2024 in the context of the newly established major in Rehabilitation and Inclusion of the Health Sciences and Technology (HST) curriculum at ETH Zurich, is a hands-on, project-based course introducing students to the principles of iterative UCD and diverse disciplines and skills of importance in the field of AT (e.g., mechanical design, programming skills, accessibility, and the translation of user needs into technical requirements). Beyond those subject- and method-specific skills, the project-based nature of the course also promotes social and personal competencies, such as teamwork and critical thinking, as identified of crucial importance by the ETH Competence Framework (ETH Zurich, 2024; La Cara et al., 2023). In groups of four, students without an engineering background work with a person with a physical disability (challenger) to develop and evaluate a personal technical solution for a real-world challenge. The challengers were recruited through our extended network. Notably, the challenges tackled during the course are not intended to solve big problems across a broad population but are based on personal hurdles the individual challengers encounter in their daily lives or during leisure activities. Accordingly, due to the strongly personal nature of the challenge, the interaction between students and challengers goes beyond engagement or consultation only. Instead, the challengers are strongly involved during the whole design process, and critical design decisions should be taken together, following the principles of co-design and even co-production, the highest levels of user involvement on the ladder of co-production (Think Local Act Personal & National Co-production Advisory Group, 2021). Following this approach, we expect that meaningful and usable solutions can be created which, ideally, are kept by the challengers and used in their daily lives after the end of the course.

This work describes the course format and outcomes of the first edition of the ETH ‘Assistive Technology Challenge’. Further, based on the results of an online survey, it reports on and discusses the students' assessment and perception of the course. As a primary outcome, the survey investigated whether the challenge-based format of the course positively affected students' motivation and the learning of transferable competencies. As a secondary outcome, the transferability of the used skills, i.e., the students' perceived relevance of the course content for their project and their future career, was investigated.

Methods

Course design and schedule

When participating in the AT Challenge, students will:

- Create innovative assistive technologies for a real-world use case.
- Evaluate the usability and effectiveness of their developed solutions.

To do so, they will learn to:

- Understand key concepts of UCD and accessibility.
- Analyze the specific needs of individuals with disabilities in real-world scenarios.
- Apply UCD principles, accessibility guidelines, and engineering principles such as design thinking, product innovation, and rapid prototyping.

A summary of the most important course information is provided in Appendix A. During the course, the students are guided through (at least) two iterations of a UCD process. Each full iteration consists of five distinct phases: ‘empathizing’, ‘defining’, ‘ideating’, ‘prototyping’, and ‘evaluating’, as depicted in Figure 1, corresponding to the respective working phases during the semester. The course follows a similar structure and aims as the ‘Assistive Technology Challenge’ organized by the HackaHealth Association as part of the MAKE Initiative at EPFL Lausanne (École Polytechnique Fédérale de Lausanne & Association HackaHealth, 2024). However, the course at EPFL mainly targets engineering students, whereas the course at ETH Zurich is designed for HST students without an engineering background. Accordingly, an important additional element of the course at ETH Zurich is to equip students with the necessary engineering skills and tools to enable them to design and build functional prototypes and to design course materials (e.g., templates for deliverables) that build upon the students' background.

The course schedule and the respective covered phases of the UCD process are listed in Table 1. The first half of the semester consisted mainly of applied lectures and hands-on workshops to provide students with the practical tools and skills required for their project. The workshops were held during two weeks, with three workshops happening simultaneously, see Table 1, i.e., Workshops I (User-centered design & usability; mechanical design & manufacturing; electronic prototyping) and Workshops II (Electrical design & manufacturing; coding; audiovisual documentation). Students were asked to attend the workshops they deemed most relevant for their specific task in the project, whereas the lectures were targeted at all students. In parallel to the lectures and workshops, the students started to work independently on their project. In the second half of the semester, the time was dedicated entirely to independently working on their project. During the regular lecture and exercise slots, on-site support from the supervisors was provided, including scheduled progress meetings every two weeks. Additional support outside those slots was offered upon request, either via email or scheduled extra meetings. In the last week of the semester, the closing event took place, where the videos and prototypes were showcased to challengers, other students, external guests, and the teaching staff.

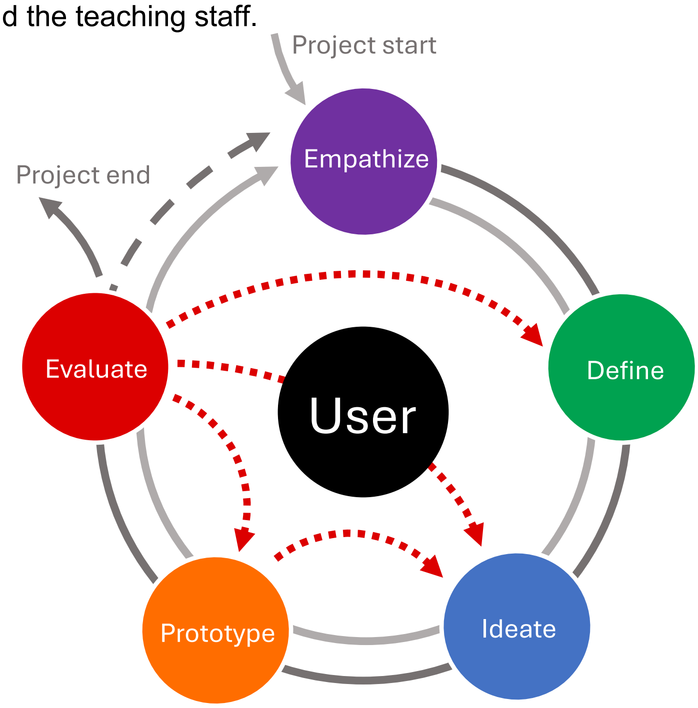

Figure 1: User-centered design (UCD) model. In an iterative process consisting of multiple cycles (grey circular arrows), the technology maturity is continuously improved. Each cycle consists of five phases: empathize, define, ideate, prototype, and evaluate. The intended target user is involved in each of those phases. In addition, the evaluation or prototyping phase can initiate smaller iterations leading back to previous phases (red dashed arrows). Adapted from Meyer, 2022.

Week	Lecture	Exercise	Graded deliverables	Phase in UCD process
1	Introduction	Teambuilding	n/a	n/a
2	Project management	Workshops I	Project plan	Empathize
3	Digital accessibility	Workshops II	List of requirements*	Define
4	User-device interaction demos		n/a	Ideate
5	Office hours		Budget plan	Ideate/ Prototype
6	Risk assessment	Office hours	n/a	Prototype
7	Office hours		1st requirement evaluation* Video idea	Evaluate/ Empathize
8	Midterm presentations		Risk analysis	Define/ Ideate
9	Office hours		n/a	Prototype
10			Video script	Prototype
11			n/a	Prototype
12			2nd requirement evaluation*	Evaluate
13			Video rough cut	n/a
14	Final video presentations and demos		Final prototype Final video	n/a

*Table 1: Course schedule covering the 14-week semester. Colours indicate the respective phases in the UCD model according to Figure 1. *Deliverables based on mandatory in-person meeting with the challenger.*

Learning assessment

The students' final grade was based on four equally weighted aspects, each assessed by the lecturers and teaching assistants using customized grading rubrics: i) the handed-in deliverables, following a typical project management structure (project plan, budget plan, list of requirements, two iterations of requirement evaluation, risk analysis), ii) the working phase during the semester (e.g., organization, teamwork, and communication), assessed based on progress meetings and interaction of students with supervisors, iii) the final video including relevant accessibility features (e.g., subtitles, audio descriptions, appropriate colour contrasts, etc.) showcasing the challenge, the development process, and the description of the final prototype, and iv) the final prototype.

Survey design

To capture the students' personal perception related to their perceived learning, motivation, and skill transferability, a self-assessment survey was administered. The survey was performed at the end of the semester after students received their project grades. The survey consisted of 16 questions covering five main themes: perceived relevance of individual lectures and workshops, factors influencing students' motivation for the course, factors affecting a successful project outcome, competencies learned, and overall perception of the course. The questions were phrased based on previous surveys performed with students (Gassert et al., 2013), on the feedback from an expert in teaching and learning at the university level, as well as on the 'ETH Competence Framework' (ETH Zurich, 2024; La Cara et al., 2023). All questions were checked for understandability and face validity by both authors.

All questions were answered on a 5-point Likert scale or as free text. Respondents had the option to skip any question or to add any additional comments. The detailed survey questions can be found in Appendix B.

Data collection and analysis

The survey was administered using the online tool SelectSurvey.NET v5.0 (ClassApps Inc., Appolo Beach, FL, USA) in July 2024, i.e., 1-2 months after completion of the course. All 12 students who participated in the course were invited via email to participate. Data analysis was performed in Python, and no statistical analyses were performed due to the low and varying sample sizes.

Results

Course outcomes

During the final week of the semester, all three groups were able to showcase their work in a video (Rehabilitation Engineering Laboratory ETH Zurich, 2024), a physical demonstration, and handed over a working prototype to their challenger. However, all groups and challengers identified some room for improvement or additional functions of the prototype which would be useful to implement if the project were to continue.

No dropouts occurred, i.e., all 12 students who enrolled in the course also completed it. During the official course evaluation conducted by ETH, students reported an average overall satisfaction with the course of 4.3 out of 5 (standard deviation sd=0.9, N=8) and an average weekly workload between 8 and 15 hours.

Survey outcomes

Survey completion

Eight out of 12 enrolled students completed the survey. For each project team (consisting of four students each during the semester), at least two and at most three responses were received.

Factors influencing students' motivation

Students reported that the project-based nature of the course, compared to a more traditional course format (e.g., regular theoretical lectures and on-paper exercises), contributed highly to their overall motivation for the course (average 4.875 out of 5, sd=0.33). A similarly high contribution to the motivation was stated as a result of the real-world challenge (average 4.75, sd=0.43) and the prospect that the resulting prototype will actually be used by someone after completion of the project (average 4.875, sd=0.33).

Learned competencies

The competencies learned/used by the students, grouped according to the ETH competence framework (ETH Zurich, 2024; La Cara et al., 2023), are listed in Figure 2. Students reported to have used or learned competencies from all groups, but more for social (communication, cooperation and teamwork, leadership and responsibility) and personal (adaptability and flexibility, creative thinking, critical thinking) than for subject-specific (mechanical design and manufacturing, electrical design and manufacturing, accessibility, assistive technology needs, user-centered design, risk management) and method-specific competencies (project management, problem-solving, decision-making, video editing). Social and personal

competencies were considered more relevant than subject- or method-specific ones for the students' future careers but were also considered less challenging during the project.
The specific competencies reported to have been learned/used the most were ‘user-centered design’ and ‘cooperation and teamwork’ (mean 4.5 out of 5), and the least learned/used was ‘video editing ‘(mean 2.88). The challenges related to the respective competencies during the project were considered the highest for ‘risk management’ (mean 3.71) and the lowest for ‘cooperation and teamwork (2.62). The competencies ‘communication’, ‘cooperation and teamwork’, ‘creative thinking’, and ‘critical thinking’ were considered to be the most relevant (mean 4.75), and ‘video editing’ was considered the least relevant (mean 1.8) for the students' future career.

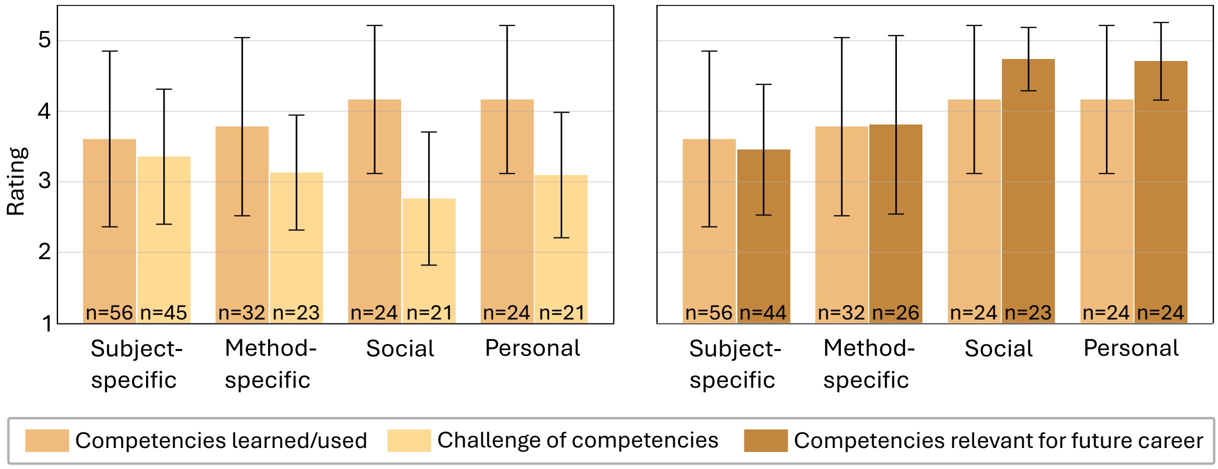

Figure 2: Learned competencies during the course compared to related challenges and their relevance. Left: Used/learned competencies during the course compared to the challenge students perceived for each competency. Right: Used/learned competencies during the course compared to the expected relevance of the respective competencies for the students' future career. All ratings were given on a range from 1 (not at all) to 5 (very much). Coloured bars indicate mean value across all responses and all competencies related to a specific group according to the ETH Competence Framework. Error bars indicate mean ± standard deviation. Number of responses per group (n) differs due to varying number of competencies per group and instructing students to answer only for competencies they learned/used during the course, i.e., those aligned with their specific assigned task within their project.

Influence of deliverables on project outcomes

The influence of individual deliverables across the semester on helping the students to structure their project to achieve a successful project outcome is given in Figure 3. All deliverables were considered to have an average influence between 3.25 out of 5 (sd=1.28, Final video) and 4.0 (sd=1.07, List of requirements). Two selected quotes from the free text comments are provided below:

- *‘Having the deadlines for the different deliverables was very helpful. As we never did such a project before, it was good that someone else told us when to do what. The deadlines were like a guide through the whole project.’*
- *‘I liked the idea of an assistant help (was also very necessary), but during the meeting with the challenger, the assistant was sometimes too much involved (like an additional team member).’*

Figure 3: Influence of deliverables on project outcomes. Influence of deliverables on helping the students to structure their project to achieve a successful project outcome on a range from 1 (not at all) to 5 (very much). Bold lines denote mean value across responses. Transparent areas indicate mean ± standard deviation (n=8).

Perceived relevance of lectures and workshops

The perceived relevance of the individual lectures and workshops is shown in Figure 4. The ‘Electrical design and manufacturing’ workshop was considered to have the highest relevance for the project (mean 5 out of 5, sd=0, n=3) as well as for the students' personal interest/professional future (mean 4.66, sd=0.57, n=3). For the project, the ‘Web- and app-accessibility’ lecture was considered to have the lowest relevance (mean 2.43, sd=1.40, n=7), for personal interest/professional career, the ‘Risk assessment’ lecture was considered to have the lowest relevance (mean 2.86, sd=1.07, n=7).

The absolute differences between the perceived relevance of the individual lectures/workshops for the project and their relevance for the students' personal interest or professional future ranged between 0.08 and 1.23 (mean 0.6). The largest differences were found for the ‘Risk Assessment’ lecture (more relevant for the project than interest/professional future) and the ‘Web- and app-accessibility’ lectures (more relevant for interest/professional future than for the project). Two selected quotes from the free text comments are provided below:

- *‘The Web- and App Accessibility and User-Device Interaction lectures were nice to hear a little bit about, but overall, it was too long, and the subject was not covered in enough depth for me.’*
- *‘Workshop session 2: Coding would have been very relevant for me but didn't cover the topic enough to be of much help for the project.’*

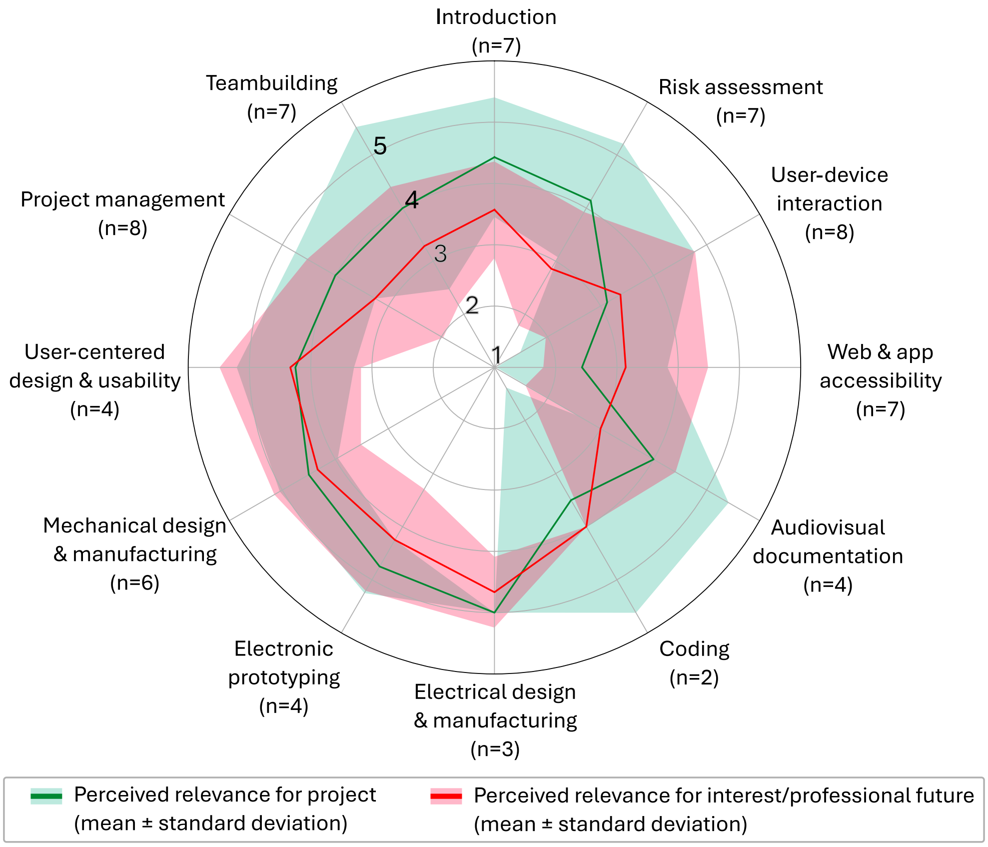

Figure 4: Perceived relevance of lectures and workshops. Relevance for project (green) and for personal interest/professional future (red) on a range from 1 (not relevant at all) to 5 (very relevant). Bold lines denote mean value across responses. Transparent areas indicate mean ± standard deviation. Numbers of responses per lecture/workshop (n) differ, as not all students attended each lecture/workshop.

Discussion

This work provides a comprehensive overview of the newly established 'Assistive Technology Challenge' course, in which students without an engineering background worked together in teams with a person with a physical disability to develop and evaluate a personalized technical solution for a real-world challenge. Further, it reports on the results of a survey conducted with students who have attended the course to inform about their motivation, their perspectives on the course format and content, and the competencies they learned during the course.

The students stated their motivation for the course as very high overall. Specifically, the project-based format of the course was reported as highly beneficial to their motivation. The fact that the course addressed a real-world challenge, and that the outcome might be used in someone's real life after the course completion had a similarly high, but not higher, impact than the project-based format. While both project- and challenge-based learning are considered strong drivers of motivation (ETH Zurich, 2024; La Cara et al., 2023), we had expected that the real-world challenge would contribute more strongly to the overall motivation. However, as project-based learning alone was already stated to be highly beneficial, this deviation can most likely be explained by a ceiling effect.

The course primarily aimed to teach students about the importance of UCD and accessibility, as well as the analysis of user needs and the application of relevant engineering principles such as design thinking, product innovation, rapid prototyping, and usability evaluation in order to receive a successful outcome. However, according to the ETH competence framework, it is not only desirable to equip students with subject-specific competencies, but also method-specific, personal, and social competencies are expected to be relevant for their future careers (ETH Zurich, 2024; La Cara et al., 2023). In the survey, students reported moderate to high learning and use of competencies across all groups. However, as the students' competencies at the beginning of the course were not recorded, it is not possible to make a meaningful estimate of the learning through the course alone. Still, interestingly, social and personal competencies were reported to have been used or learned even more than subject- or method-specific competencies. This is surprising, given the hands-on nature of the projects relying strongly on accessibility, user-centered design, and engineering. However, it matches the findings that students expect those competencies to be more relevant for their future careers. It is further well aligned with the fact that social and personal competencies have been identified to become the most in-demand competencies in the professional world within the coming years (La Cara et al., 2023). Previous research indicated that students who do not have any hands-on project experience often struggle or feel insecure about proactively learning new skills (Du et al., 2019). While some students mentioned similar concerns at the beginning of the semester, the challenges related to individual competencies were reported to be generally low, indicated otherwise at course completion. This suggests that students tend to underestimate their capabilities to quickly acquire new skills and apply them effectively.

The course content was generally perceived positively and considered mostly relevant for the students' future careers. Specifically, the deliverables, which were defined based on typical tasks when managing an (engineering) project, were acknowledged and appreciated by the students as guidance throughout the project. Still, the actual influence of the deliverables on a positive project outcome was mostly rated as being only moderate to slightly positive. According to oral feedback from the students during the course, preparing the deliverables required a lot of time and effort. Hence, the deliverables might have distracted them from working on developing their technical solutions, thus decreasing the overall positive influence. Most of the lectures and workshops were considered highly relevant for both the project and students' future careers. This good alignment suggests that the course format is well suited to promote the transfer of the learned skills to the students' careers. The reported high relevance of the more technically oriented lectures and workshops for their future careers might be interpreted twofold: on the one hand, the experience that students gained in this area during their previous education might not have been perceived as sufficient for their intended career. On the other hand, this course might have encouraged students with a background in health sciences and technology to consider more technically oriented careers. However, both of these assumptions need to be taken with care and would need to be confirmed with dedicated questions in a potential follow-up survey. It should be underlined that, by the course design, some of the workshops were not attended by all students but were selected by the students themselves based on their prior experience and their focus area within their specific project. Also, not all projects required the same competencies, i.e., some of the workshops were already expected to be irrelevant for specific projects, likely explaining the high variability in responses. The risk assessment lecture was perceived as having little relevance for the students' professional future. This was surprising, given that analyzing the risks of any device or procedure is generally considered a crucial part of every development project. When human users are involved, analyzing the risks to ensure safety is even more important (Bahr, 2018). Accordingly, the lecture either did not sufficiently underline the topic's importance, or its content was not perceived as useful for students to transfer the knowledge to future projects.

The survey results should be interpreted with care due to multiple reasons. With only two thirds of the students who attended the course filling in the survey and not all students answering all questions (e.g., since students were responsible for different aspects of the project, which was intended by the course design), the sample size for some of the questions was relatively small with high variability. The time gap of 1-2 months between completion of the course and the survey could have resulted in a recall bias. Further, when filling out the survey, students had already received their final grades. While this was done on purpose to avoid any risk of biasing the grading based on the survey responses, the received grades could have affected the responses by students. Lastly, there might have been a social desirability bias due to the strong interactions and resulting personal connections built between course organizers and the students during the semester, leading to overall more positive responses.

Conclusion

Overall, teaching not only the principles of user-centered design, but also engineering competencies in dedicated workshops enabled students without any previous engineering background to achieve a successful project outcome, achieve high student motivation, and strengthen their competencies in fields expected to be relevant for their future. This will hopefully equip HST graduates with appropriate tools to fill the missing link between engineers and end-users in the AT- and healthcare sector.

The learnings gained during the first edition of this course and through the survey can also help to shape future educational formats in various disciplines. Specifically, the following aspects should be considered when aiming to transfer a similar course format to a different academic setting.

- Framing the project around a real-world challenge, which includes the building of a personal connection between the students and the intended recipient of the project outcome, promotes students' engagement and motivation.
- Making social and personal competencies an integral part of the project and clearly communicating this to the students fosters the learning of those competencies. This is expected to be most relevant for students' future careers.
- Offering the course to a small number of students allows for targeted supervision tailored to the individual projects and teaching of the specific competencies required for the diversity of the offered challenges. Accordingly, if a similar course should accommodate a notably larger number of students, the offered projects would need to pursue a common challenge, and significantly more resources (e.g., workshop access, supervisors, hardware budget) would need to be provided.

Implementing course formats similar to the Assistive Technology Challenge in a study curriculum may contribute to a higher educational quality in project- or challenge-based learning and, therefore, optimally prepare students to conduct highly interdisciplinary projects in their future careers.

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The survey was conducted anonymously and approved by the ETH Ethics Commission (2024-N-210).

Appendix A: Course summary FS24

Abstract (see course catalogue)	Assistive technologies can increase the independence and quality of life of persons with disabilities. This hands-on, project-based assistive technology challenge exposes students to the user-centered design of a dedicated assistive technology solution adapted to the specific needs of a person with disability and prepares them for a career in the field of assistive and medical technologies.
Learning objective (see course catalogue)	• Expose students to user-centered design of an assistive technology adapted to the needs of a person with disability. • Understand the principles of user-centered design, storyboarding with personas, and usability evaluation and be able to apply these principles in a real-world use case. • Get introduced to topics relevant to the field of assistive technologies such as needs definition, accessible design, web/app accessibility, and assessing solution efficiency. • Get introduced to relevant engineering topics such as design thinking, product innovation and rapid prototyping.
Content (see course catalogue)	The course covers the interdisciplinary topics relevant to the development of assistive technologies, including user needs derivation, innovation and rapid prototyping, user-centered design, usability, and efficiency evaluation. It is framed around a user-centered design challenge for a real-world use case (in groups of four students) in tight collaboration with persons with disabilities (challengers), with the goal of realizing an assistive technology solution adapted to the specific needs of each challenger.

Target group	MSc in Health Sciences and Technology
ECTS	6
Weekly hours	Scheduled: 4 hours Independent work: ~6-8 hours
Number of students	12
Number of groups	3
Number of lecturers	2, plus guest lecturers
Number of teaching assistants	2
Provided infrastructure and resources	Access to fully equipped makerspace (manual tools, power tools, 3D printers, lasercutters) Budget: CHF 600

Appendix B: Survey Questions

1. In order to be eligible to participate in the survey, you must first confirm the following statement:
   - □ I confirm that I was enrolled in the course 376-1224-00L Assistive Technology Challenge at ETH Zurich during the spring semester 2024.
2. Which project did you work on? (Be aware that answering this question will make your responses less anonymous.)
   a. Daniele
   b. Giuliano
   c. Lila
   d. Prefer not to disclose

All of the following questions are to be answered on a 5-point Likert scale, each with optional space for free text comments

3. How relevant did you find the following lectures/workshops for your specific project? (answer only for attended lectures/workshops)
   a. Introduction
   b. Team building
   c. Project Management
   d. Workshop: Usability & user-centered design
   e. Workshop: Mechanical design & manufacturing
   f. Workshop: Electronic prototyping basics
   g. Workshop: Electrical design & manufacturing
   h. Workshop: Coding
   i. Workshop: Audiovisual documentation
   j. Web & app accessibility
   k. User-device interaction
   l. Risk Assessment
4. How relevant did you find the following lectures/workshops in view of your personal interests and/or professional future? (answer only for attended lectures/workshops) *(same options as in question 3)*
5. How much did the fact that the projects focused on a real-world problem of a challenger contribute (positively) to your overall motivation for the course?

6. How much did the fact that the result of the project might be actually used in someone's real-life contribute (positively) to your overall motivation for the course?
7. Comparing to a more traditional course format (e.g., regular theory lectures and on-paper exercises), how much did the project-based format contribute (positively) to your overall motivation for the course?
8. Comparing to a more traditional course format (e.g., regular theory lectures and on-paper exercises), how much did the project-based format contribute (positively) to your understanding of the potential and challenges in the field of Assistive Technology?
9. How much did the regular deliverables help you in structuring your project to get to a successful result?
    a. Project plan
    b. Budget plan
    c. List of requirements
    d. List of requirements / evaluation iteration 1
    e. List of requirements / evaluation iteration 2
    f. Risk analysis
    g. Final video (including idea, script, and rough cut)
10. How much did the regular progress meetings with your assistant help you in structuring your project to get to a successful result?

11. To what degree do you feel like you learned/used the following competencies during the course?
    a. Mechanical design
    b. Mechanical manufacturing (e.g., 3D-printing)
    c. Electrical design
    d. Electrical manufacturing (e.g., soldering)
    e. Accessibility / assistive technology needs
    f. User-centred design
    g. Risk management
    h. Project management
    i. Problem-solving
    j. Decision-making
    k. Video editing
    l. Communication
    m. Cooperation and Teamwork
    n. Leadership and Responsibility
    o. Adaptability and Flexibility
    p. Creative Thinking
    q. Critical Thinking
12. Comparing the competencies you brought into the project to the competencies you had to learn during the course, how challenging were the tasks you encountered? (answer only for competencies relevant to your tasks within the project)
    (same options as in question 11)
13. To what degree do you expect the following competencies you used/learned during the course to be useful in your future career/projects? (answer only for competencies relevant to your tasks within the project)
    (same options as in question 11)
14. Could you imagine working or performing research in the field of Assistive Technology someday?
15. Would you recommend attendance of the course to your peers?
16. If you had to pick only one, what aspect/moment of the semester will likely stick in your mind the longest and why? E.g., the most surprising, most challenging, most fun, biggest learning… could be anything!
    (Free text only)

How to develop and implement teaching projects in outdoor education

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Abstract

Learning through projects can raise interest and motivation, and support the construction of competencies, disciplinary, and interdisciplinary knowledge via working on real-life problems in realistic settings. One form of project-based learning is outdoor education, that is, situating learning and instruction in settings outside the regular classroom. We present a course for students in the teacher education program at ETH Zurich that implements project-based education on two layers: the course itself is project-based, and the pre-service teachers create project-based outdoor teaching units during the course. We describe how we balance freedom and guidance, and scaffolding in the course design. In addition, we report how students respond to and evaluate our course, and discuss challenges and opportunities for lecturers. By presenting sample projects and insights from the implementation and continuous development of the project-based course, we aim to inspire and guide lecturers at ETH Zurich and other universities who consider implementing project-based courses in their teaching.

1. Introduction

Authentic project-based learning environments can serve as an effective and motivating instructional approach in higher education. Learning through projects has the potential to stimulate learners' motivation and interest, benefit the construction of diverse knowledge and both intra- and interpersonal competencies simultaneously, and allow learners to get in contact with authentic challenges and demands they will encounter in their future work (e.g., Boss & Kraus, 2018; Chen & Yang, 2019; Wijnia, et al., 2017; Wijnia et al., 2024; Zhang & Ma, 2023). However, to realise this potential, project-based learning environments need to balance freedom of the learners with teacher guidance and scaffolding. Achieving this balance is of particular importance for outdoor project-based learning (for a broad overview of outdoor learning see Jucker & Au, 2022).

In this article, we describe a course that implements outdoor project-based learning in the teacher education program at ETH Zurich. Essentially, this course makes use of project-based learning on two layers: A) Our students who will become Gymnasium teachers in STEM subjects are tasked to create a teaching unit that they could perform with Gymnasium pupils (the Gymnasium is the highest secondary school track in Switzerland which, after successful graduation, provides direct access to universities). B) We organize the whole course to result in a project-based outdoor weekend, for which the students also need to prepare food and

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shelter. This format follows a train-the-trainer structure[2], insofar as it aims to enable pre-service teachers to conduct outdoor learning in their future job.

In the following, we first discuss foundations of outdoor project-based learning in general, and the peculiar aspects that need to be considered. Afterwards, we describe our course. In the third part, we reflect on our experiences over several iterations of the course and we discuss how our specific experiences may inform other outdoor-based learning opportunities such as field trips and excursions.

1.1 Foundations of outdoor project-based learning

Project-based learning can have a substantial effect on learners' motivation (Wijnia et al., 2024) and academic achievement (Chen & Yang, 2019) compared to traditional instruction but needs to be implemented carefully taking various pitfalls into account to be effective. The first differentiation regards the type of outdoor learning (Rickinson et al., 2004; see also Imhof, 2016): Outdoor learning activities that focus on adventures can be categorized as *outdoor adventure activities*; learning activities that are carried out in the immediate school environment can be categorized as *school ground and community projects*; and learning activities that involve visiting a place to explore something can be categorized as *fieldwork and outdoor visits*.

Outdoor project-based learning could be subsumed under the fieldwork and outdoor visits category. However, it does not put a specific site in focus, but focuses on how to plan and implement project-based learning. Outdoor project-based learning is typically interdisciplinary, and results in a product at the end of the unit (e.g., a soup, a catapult, a solar cooker, a pyrolysis cooker, a drawn map; see Table A1).

In so-called WEIRD (westernized, educated, industrialized, rich, democratic) countries, formal education in schools and universities mainly takes place indoors. However, outdoor learning warrants itself for some topics, that either cannot be taught indoors for practical reasons (e.g., shooting a water rocket as high as possible) or that offer a direct experience 'in-vivo' (e.g., which plants are growing in this area). Ayotte-Beaudet et al. (2017) identified two main reasons for outdoor education: increasing environmental concerns and enhancing science education. The idea is that knowing one's environment is a prerequisite for protecting it. Project-based learning that is based on real-world problems and allows for reflection is also an important component of transformative learning (e.g., Getzin & Singer-Brodowski, 2016). Another strength of outdoor education is that it allows for drawing links between subject areas, enabling interdisciplinary projects. Table A1 in the appendix lists examples of teaching units from various iterations of our course illustrating how different topics and subjects can be combined.

Implementing project-based learning in an outdoor setting is typically more resource-intensive than staying indoors. For example, travel needs to be organised, potential safety issues assessed, and materials transported. Ayotte-Beaudet et al. (2017) list several challenges that teachers meet when organizing outdoor education, ranging from planning concerns to inadequate preparation and a lack of time. We suggest that these additional requirements should not be seen as additional costs, but rather as part of project-based learning given that its aim is to learn with authentic challenges. Making challenges authentic often requires leaving the classroom. Besides the higher resource intensity, planning outdoor project-based learning needs to consider four aspects: structure and alignment, assessment challenges, situatedness, and equity issues. We will discuss these four aspects using the building a solar cooker as an example (see Figure 1).

[2] We thank an anonymous reviewer for this categorization.

Figure 1: Self-Made Solar Cooker constructed out of a cardboard box, aluminium foil, transparent film, and glue.

1.2 Structure and alignment

Project-based learning activities need careful instructional preparation, similar to other forms of instruction. Biggs (1996) coined the term ‘constructive alignment’ for this requirement. He emphasized the necessity of aligning the courses’ objectives (learning goals), the teaching/learning activities, and the assessments *for* learning (i.e., formative assessment, Black & Wiliam, 2009) and *of* learning (i.e., summative assessment, Edelsbrunner et al., 2021). When planning project-based learning activities, the first step is thus to reflect upon the objective(s). What knowledge and competencies are learners expected to acquire through the course? In outdoor education, there are often multiple, intertwined objectives. For example, in our outdoor education course, we have the overarching aim that the students will develop learning materials suitable for an outdoor setting. In addition, they should develop social competencies in jointly planning an outdoor weekend and methodological competencies in how to structure an outdoor weekend, what aspects need to be considered, what resources are needed (e.g., setting up a camp, organizing cooking, anticipating dangers and how to deal with them), and how the outdoor units can be embedded in the ‘normal' instruction (e.g., how it is prepared in the classroom and how the experiences from the outdoor units can be used in subsequent classroom lessons). With regard to the solar cooker example, the learning goals comprise that the learners can explain how sunlight can be used for heat generation, that learners can distinguish between different types of heat transfer (conduction, radiation, and convection), and that learners are able to build simple solar cookers themselves.

To align learning goals, instructional methods, and assessment(s), we recommend following a structured approach. Numerous frameworks or models (e.g., Biggs, 1996; Koedinger et al., 2012) and taxonomies of learning goals (e.g., Anderson et al., 2000; Bloom et al., 1956; Marzano & Kendall, 2006) aim to enhance and streamline planning of instruction. Each framework and taxonomy possesses unique strengths and limitations. Despite variations in terminology and structure, these frameworks and taxonomies are not fundamentally distinct. Rather, they seek to convey the same core principle – constructive alignment – but use different levels of granularity. Greutmann et al. (2020) synthesized the existing frameworks and taxonomies with the aim of providing a *pragmatic lesson planning taxonomy*. To make it pragmatic, that is, useful and manageable for everyday teaching, the pragmatic lesson planning taxonomy is less fine-grained than other taxonomies. However, it remains in accordance with the current state of research on learning and instruction. We assume that most educators are familiar with a taxonomy of learning goals. Given that no empirical research has yet competitively tested the taxonomies against each other, we refrain from recommending one. However, for planning and designing project-based learning activities, we urge educators to follow the core principle (constructive alignment) supported by a taxonomy of their choice: define learning goals, plan suitable instructional formats to achieve the goals, and plan the assessment of the achievement of the goals in advance.

Designing effective teaching projects for outdoor education requires not only following a structured lesson planning process, but also providing a clear structure regarding the environment in which these projects will take place: outdoors! In formal educational settings in Switzerland and Central Europe, most teaching takes place in school or university classrooms. In such cases, the room itself provides a well-structured environment. Entering and leaving the room can be seen as a *temporal* structure; the way how tables, chairs, projectors, whiteboards etc. are arranged provides *spatial* structure. Learners are used to rules or norms that structure the interactions in such classrooms – in pedagogical terms, the environment can be thought of as a third teacher (e.g., Strong-Wilson & Ellis, 2009). When teaching takes place outdoors, these familiar structures no longer exist. Thus, it is important to explicitly negotiate and define rules with the learners before going outdoors. Educators need to be aware that they have less control and learners have more freedom. Thus, precise schedules are necessary to provide orientation for all – where are we at what time? To make outdoor project-based learning effective, this planning needs to be part of the constructive alignment from learning goals to assessments.

1.3 Assessment

Assessment is necessary to make learning and competence development visible. This also holds for outdoor education. Based on the idea of constructive alignment, assessment should be designed during the instructional planning so that it aligns with the learning goals and the instructional setting and will thus provide valid information on whether learners reached the goals.

With regard to planning and implementing outdoor education, assessment thus requires adaption to the specific setting: Firstly, practical aspects are to be considered such as that it is often not possible for the learners to write and take notes (or complete formative assessment tasks). Formative assessment therefore needs to use other modes of indicating responses (e.g., fingers/hands, cards, or digital devices). Secondly, in contrast to learning in traditional formats, learners are at first glance more active in project-based learning, e.g., moving around, sitting in groups and chatting, building something following an instruction. However, superficial activity, such as following the steps of an instruction to create a solar cooker does not necessarily imply cognitive activation. Cognitive activation denotes that learners think and reflect on what they are doing (e.g., Schumacher & Stern, 2023). When they build a solar cooker, the instructional aim is typically not to just build it, but to understand why certain steps make a good solar cooker, why it works and so on (i.e., the learning goals), how it could be adapted if surrounding conditions change (e.g., strong wind picks up; clouds alternate with sunshine). Thus, it is important to not equate learners' overt active behavior in outdoor education with covert learning processes (Thurn et al., 2023). To promote cognitive activation, it is necessary to structure the outdoor learning activities accordingly. They need to include prompts to make learners think about what they are doing. These prompts should be defined or formulated based on the learning goals. At the same time, these prompts can also be used by the educator for formative assessment: Do the learners understand why a particular design of the solar cooker makes it more effective than another design? What physical principles capture this effectiveness? Taken together, we advocate that outdoor project-based learning is accompanied by formative assessments to scaffold and focus learners, and to make progress and learning visible to educators and learners.

With regard to conducting summative assessment in outdoor project-based learning, we want to stress that summative assessments need to fulfill several requirements, for example, they should be objective, reliable, and valid (for an overview see Edelsbrunner et al., 2021). Being outdoors can pose difficulties in having standardized and comparable conditions for each learner as the environment is much less controllable in comparison to the indoor classroom. At the same time, outdoor project-based learning should be embedded within the standard curriculum – it should be prepared and followed up in the classroom. For example, a summative assessment could consist of having learners collect and document their experiences made outdoors when returning indoors in the form of presentations, papers, or portfolios. These products could be used for summative grading purposes.

1.4 Situatedness

Learning is situated, at least to some extent (e.g., Anderson et al., 2000; Thurn & Daguati, in press). That is, learning occurs in specific situations at specific times, and these specificities are remembered together with the actual content to be learned. Accordingly, learners will often remember the specific project, where it took place and under what circumstances. On one hand, this often results in well-remembered events, as outdoor-projects are so different from the usual context. On the other hand, this situatedness may hinder the flexible transfer of the acquired knowledge and competencies to other projects, everyday demands, or subsequent learning within the classroom (e.g., Engle et al., 2012).

Two distinct transfer challenges emerge in outdoor education. The first challenge occurs when learners go outdoors: They will do activities and work on projects for which they will need knowledge and competencies that they acquired in the regular classroom. When the outdoor project is finished and the learners return to the classroom, the second challenge occurs: Learners need to transfer the knowledge and competencies developed outside to inside the classroom. These two challenges are important to consider when planning outdoor education projects. Educators shall prepare with the learners why they will be doing certain outdoor activities and how these activities build upon the classroom instruction. After returning to the classroom, educators need to support learners in connecting their outdoor experiences with their subsequent indoor learning. As Engle and colleagues (2012) posit, the educators need to create an expansive framing connecting in- and outdoor, that is, being explicit about how knowledge is useful and can be applied in different contexts – for example, how the knowledge constructed in classrooms is important for the outdoor projects, how the outdoor project benefits understanding of general science principles, and why the project matters for continuing education in the classroom. Regarding the solar cooker, when dealing with the topic of solar energy use, educators could introduce the necessary prior knowledge about light absorption, heat transfer, heat radiation in class, and then proceed to the outdoor project of building a solar cooker (if there is not much time outdoors, cookers could be built indoors). By building different solar cookers, the learners can compare and contrast different types, helping them to overcome situated knowledge. Then the cookers are tested outdoors, where they may perform differently in different weather conditions. Back in class, the educator can connect the practical experience of building the solar cooker to the general topic of solar energy use. Again, these aspects highlight the necessity of planning based on constructive alignment. Moreover, it is helpful to communicate the learning goals to the learners (e.g., Reed, 2012) so that they know what the instructional focus of the outdoor project is and receive an advance organizer (e.g., Ausubel, 1960; Mayer, 1979). Optimally, the learning goals connect in- and outdoor learning to achieve expansive framing and thus counter situatedness and foster transfer.

1.5 Equity issues

Learners in project-based learning environments work together and co-create knowledge. They have different backgrounds, interests, knowledge, and competencies. Taking this diversity into account is highly important in outdoor education. Some learners may have a lot of experience being outside, others may spend most of their time indoors. Some may be afraid of certain things, others appreciate and seek challenges. These interindividual differences have to be considered when planning project-based outdoor education.

The heterogeneity of learners is an asset for outdoor education which is often based on group activities, cooperative, and collaborative learning. Learners can benefit from diversity when solving problems or building something together (e.g., the solar cooker as an energy-saving low-budget cooking device). When choosing a specific example for a general principle (e.g., solar energy use with a solar cooker), educators need to be sensitive to the fact that learners may have different interests (Berkowitz et al., 2022), especially as girls may be put off by too 'masculine' STEM topics.

It is important to help all learners achieve the desired learning goals, but also to give them the freedom to choose from a range of topics all suitable for developing the targeted knowledge and competencies and to choose the roles they want to take in group work. For example, some may be better at conceptualising what an effective solar cooker might look like, whereas others may be better at making it. One disadvantage of group activities is the strong knowledge interdependence (e.g., Deiglmayr & Schalk, 2015). That is, some learners may have some knowledge that others do not, as illustrated in the solar cooker example. Since there are typically learning goals which apply to all learners, it is important to design group activities in such a way that even if not everyone has to do everything, they at least learn what certain steps are needed for and how to achieve them. It can be helpful for the success and the acceptance of an outdoor project, if learners are involved in the planning of the activities from the beginning.

2. A course on outdoor education

At Swiss Gymnasia, project-based approaches (project weeks, field trips, etc.) are increasingly becoming part of the curriculum. Teachers are expected to acquire the competencies to design and implement projects, to guide pupils, to foster efficient group-work environments, and to ensure the transferability of the knowledge and competencies acquired through the project. Within the teacher education programme at ETH Zurich, we have therefore designed a course on creating authentic project-based learning environments. The course pursues a broad overarching learning goal: preparing these future teachers for creating and running project-based approaches themselves. The participants in our course are pre-service teachers (denoted as 'students' in the following). During the course, students work in groups and develop a teaching unit that can only be taught outdoors, but which aligns with learning goals that are part of the curriculum and taught within classrooms. From the beginning of the course, all students are involved in the overall planning of an outdoor weekend during which they will test their teaching units.

2.1 Students in our course

Per iteration 10-20 students take part in the course. Our students are enrolled in the teaching diploma studies (except for sport teachers, who follow a different study programme). They differ in their domain-specific knowledge and expertise, as they study different STEM subjects, but also with regard to pedagogical knowledge, as they can choose this seminar freely at different time points in their teacher education studies. To address the heterogeneity, we encourage the students to form interdisciplinary groups, which has often resulted in creative teaching units (see Table A1 in the appendix).

2.2 Course development

The course is an elective semester-long 2 ECTS seminar embedded within the teacher training programme. A team of multiple lecturers teaches the course. One of the authors (H.G.) has been part of the team since the course's first development, ensuring consistency and constant improvement of its instructional structure over the years.

The course comprises in-class preparatory meetings, a project-based outdoor weekend, and a feedback and reflection session (see A to C in Figure 2). The following sections provide a detailed overview of these components.

Figure 2: Course Structure.

The course places a strong emphasis on the project-based teaching units presented during the weekend. In terms of constructive alignment, our instructional method aligns with the learning goal, as it provides sufficient guidance for the future teachers to experiment with project-based learning in a safe setting. We present the learning goals and the course requirements at the very beginning. Our teaching mode combines the principles of freedom and self-directed learning with guidance and scaffolding. It requires students to constantly reflect on their project, requesting them to provide regular updates to the lecturers, while empowering them with sufficient responsibility to ensure the success of the weekend and their projects. Whereas we ask the students guiding questions to make them aware of possible difficulties, we do not necessarily provide them directly with alternatives or solutions to challenges they may encounter during the weekend. That is, it is also possible that a teaching unit that the students have created for the weekend might fail. We consider such failures valuable and productive for learning, that is, the possibility of failure is a design feature of the course (see e.g. Simpson et al., 2020). Learning through experiencing challenges or even mistakes has a high potential to provide valuable and sustainable learning experiences if the learners are prompted to reflect on challenges, failures, and successes. We however make sure that students are not failing with regard to security issues.

2.3 In-class preparatory meetings

We usually conduct three to four preparatory meetings during the semester (Figure 2A). Before the first meeting, we send a welcome e-mail to the students with an initial assignment: we require the students to identify a topic, question, or content from their subject that would be particularly suitable for project-based outdoor teaching units. The first in-class preparatory meeting starts with an introduction to the principles of outdoor education, accompanied by illustrative examples of past projects. Students are required to reflect on their own learning trajectory during school and on projects that they have experienced outdoors. Often these projects belong to the category of fieldwork and outdoor visits. We then emphasize that our course focuses on outdoor project-based learning.

By showing past projects and prompting the students to reflect on their own experiences in outdoor projects, we aim to circumvent situatedness and activate prior knowledge. Subsequently, we discuss the advantages and disadvantages of the projects they experienced in school. In this meeting, we also ask the students to form groups and share their initial ideas about topics suitable for outdoor projects.

In the second meeting, we ask the students to decide which of their ideas they would like to pursue. We provide information about the specific challenges of outdoor education regarding teaching and assessment. We also ask students to assign themselves to tasks regarding the weekend, such as planning the logistics, shopping, cooking, or waste management. To ensure efficient group work, we ask for regular updates from each group.

At the third meeting, the reconnaissance meeting (see below), the students travel to the site where the outdoor weekend will take place. This meeting is an opportunity for students to familiarise themselves with the area, and to check the feasibility of their proposed teaching unit. At this meeting, students are also required to give a short presentation of their teaching unit and to respond to questions or feedback from the lecturers and their peers in order to encourage reflection, constructive debate, and effective further development of the unit.

In the fourth meeting, we discuss final tasks, including purchasing food and beverages, cooking, and the allocation of sleeping space in tents. We encourage the students to consider all aspects of the weekend, providing only guiding input if necessary. Additionally, we inquire about potential risks or challenges such as adverse weather conditions or changes in the flora since the reconnaissance meeting. This inquiry triggers students to develop alternative plans in case of such occurrences.

2.4 Reconnaissance

In order to gain an understanding of the local conditions, it is essential that teachers conducting an outdoor project know the area where it will take place beforehand. Reconnaissance means visiting the site and the camp's surroundings and determining suitable locations for the planned activities. If a campsite is planned, it is important to check whether the infrastructure is suitable and that there are adequate cooking facilities (e.g., enough wood for a fire) and sanitary infrastructure (toilets, water supply, etc.). In addition, the list of materials is checked and completed and the transport of materials is planned, specifying the time and place. A reconnaissance is also necessary for identifying potential safety risks, such as rotten wood or dry branches that could fall down in a storm. We look out for such risks and include them in our planning. A short reconnaissance report is written to record the information gathered. In addition to the basic conditions of the weekend (arrival and departure, meeting point, location of the camp, etc.), this report contains specific information on the planned project-based teaching units and the preparation of a bad weather programme.

In the specific case of our seminar, we explore our location in Bremgarten on the river Reuss three weeks prior to the event. We chose this timing for the reconnaissance so that enough time remains to make any necessary adjustments but that the ecological conditions are likely to remain comparable to those of the weekend. Our aim is that all students take part in this reconnaissance, but sometimes students have other duties. In order to keep all students informed of the current status of the preparations, we send the reconnaissance report promptly and discuss it in the last preparatory meeting.

In addition to the reconnaissance with the students, one or two of the team of lecturers visit the site before the course starts. This allows for checking whether the overall conditions of the site remained suitable for the course (e.g., dry branches, whether the surrounding meadows have been mowed or not, and the water temperature and water level at the river). Potentially, additional measures have to be taken to use the site as planned. These visits are thus a point of reflection for the lecturers; during this visit we think through the whole course and – based on this reflection – learn about possible adaptions or improvements of our course.

2.5 Outdoor weekend

We conduct the weekend every year at the end of the spring semester (Figure 2B). To ensure maximal safety during the weekend, we have discussed and noted risks, safety issues and necessary preparations with the students beforehand (e.g., bringing sun and weather protection, protection against mosquitoes and ticks). Additionally, we adhere to the following principles on-site: we have a First Aid kit, a lecturer comes by car to be able to, for example, transport students in case of sudden illness or an injury, all students receive a printed document which compiles all safety information and telephone numbers. To cope with the low structuredness of the environment, we enforce sticking to a precise schedule: After arrival on Saturday morning, we start by setting up the tents and collecting wood for a campfire. We then remind all students about the facilities and potential risks, such as ticks in the forest. Afterwards, students have time to prepare their teaching units (e.g., setting up stations, checking for changes in the flora since the reconnaissance, checking technical equipment). After a snack for lunch, we discuss whether changes in the order of the teaching units are necessary (e.g., because of weather conditions), and then proceed with the first unit. That is, students present their teaching unit to their peers, who take the role of the learners. Each teaching unit lasts 90-120 minutes. The lecturers also participate as learners, but simultaneously take an observational perspective and take notes on the teaching unit. After each unit, the lecturers discuss what they have observed.

After two to three teaching units, the preparation of the dinner starts as a group activity. Whereas some students are responsible for lighting up the campfire, others fetch water, chop vegetables, or prepare the waste separation. The evening ends with the dinner, followed by discussions and games around the campfire.

The next morning, after camping in the woods and having breakfast at the campfire, we continue with the teaching units. For lunch, we eat the leftovers. The weekend is complemented by a team experience in which we practice river swimming at a nearby river with strong current. For homework, we ask the students to reflect on their teaching unit: what worked and what could be improved in future iterations of this unit?

2.6 Feedback and reflection session

The final session of the course takes place after the weekend (Figure 2C). We use this session for peer-feedback and feedback from us on the teaching projects. To enable the transfer from outdoor to indoor, students first present their own reflections on their teaching unit. Then their peers provide feedback and finally we voice our observations and ideas for improvement. As an (ungraded) summative assessment, students submit an essay summarizing their teaching unit and their reflections. We provide feedback on these essays.

3. Reflecting on the course

3.1 Students' evaluations

Across the years, our course has received very positive feedback. Here, we report students' feedback from the spring semester 2024. Students liked the fact that they were actively involved in co-designing the course. This course was perceived as something entirely different from other courses they had experienced so far. Students were positively surprised at how open and engaging outdoor education could be. They liked the creativity, interdisciplinarity, and variety of the teaching units. By observing the other groups' teaching units, they were able to identify elements that were effective and those that required modification. The sequence of the teaching units allowed for sufficient flexibility to adapt the units to, for example, meteorological conditions. Furthermore, the students expressed satisfaction with the feedback that they received from us. Many students highlighted the positive experience of river swimming, describing it as an engaging, professionally guided, and enjoyable activity.

As the entire focus of the preparatory sessions in-class was on planning the weekend and the teaching units, they also stated that they learned that carrying out outdoor education projects requires a lot of organization. As a result, they acquired considerable knowledge regarding organizational issues, such as packing, travel, safety, and the division of tasks. Nevertheless, some students indicated that they still did not feel confident to organize such projects with their future pupils on their own. In particular, outdoor classroom-management would require a different approach when working with secondary school pupils, in contrast to university students who are more receptive and engaged. The implementation of the teaching units with secondary school pupils would present some additional challenges and likely require some changes. Moreover, the students mentioned that it would be beneficial to receive information about the legal aspects, responsibilities, and duty of supervision in outdoor education. In terms of improvements, the students proposed that the weekend should not be held just before the end of the semester. Furthermore, they suggested that the teaching units are analysed and reflected upon directly at the weekend, for example while gathered around the campfire. We use this feedback to continuously develop the course.

3.2 Our reflections

We recognise that the course is time-consuming and resource-intensive. For lecturers being interested in organizing an outdoor weekend, we have tried to estimate the effort required for organization in Table 1.

Task	Time estimate
Seminar (preparation, teaching, reconnaissance)	20h
Weekend preparation (request authorisation for camping, contacting river swimming expert for workshop, preparing cooking utensils, wetsuits, …)	10h
Weekend itself (with 1 overnight stay)	35h
Giving Feedback to student projects	10h

Table 1: Estimated time resources per lecturer.

Even though the effort is quite high, we nevertheless believe that the benefits outweigh the costs. It is gratifying to observe how the students create interdisciplinary outdoor teaching units and how all students find the experience meaningful. The possibility to design and perform their own teaching unit, and to organize the logistics for the weekend grants the students a lot of autonomy. This is a core motivation. The resulting projects show that students take this opportunity seriously and construct creative, interdisciplinary projects (Table A1). Interdisciplinary projects are more in line with the concept of Bildung, which encompasses multidisciplinary cultivation, personal development, and maturation. By organizing the weekend, the students develop competencies in project planning, management, communication, and adaptability. Table 2 lists the competencies according to the ETH Competence Framework that our course fosters and/or assesses.

Domain	Subdomain	Status
Subject-specific Competencies	Concepts and Theories	assessed
	Techniques and Technologies	assessed
Method-specific Competencies	Analytical Competencies	fostered
	Problem-solving	assessed
	Project Management	assessed
Social Competencies	Communication	fostered
	Cooperation and Teamwork	fostered
	Leadership and Responsibility	assessed
	Sensitivity to Diversity	fostered
Personal Competencies	Creative Thinking	assessed
	Integrity and Work Ethics	fostered
	Self-awareness and Self-reflection	assessed
	Self-direction and Self-management	fostered

Table 2: Competencies addressed by our course based on the ETH Competence Framework.

Beyond these competencies of the ETH Competence Framework, the course also fosters competencies related to education for sustainable development such as anticipatory competency, competence in interdisciplinary work, and strategic thinking competency (de Haan, 2006; Rieckmann, 2011).

3.3 Transfer to other courses

Our course is in line with the Sustainable Development Goal 4 (Quality Education) particularly target 4.1. By making an extensive description of the course and examples available open-access we also contribute to the target 4.c: With this detailed description of an outdoor education course, we hope to provide ideas and inspiration for other university educators who already have experience with project-based learning methods, as well as for those who have no experience yet, but are trying to extend their teaching beyond the standard classroom. Moreover, whereas we report on a specific course, we believe that several of our insights are transferable or are at least informative for other courses and forms of instruction at school and university.

At school, outdoor education can complement indoor education. It offers possibilities for learning that are not realizable in other ways, and often it is those 'special' lessons that students keep in mind from school. Moreover, for schools implementing high quality outdoor education may become a 'unique selling point'. As stated by Ayotte-Beaudet et al. (2017), teachers often do not feel well-prepared to organize such activities. We thus urge other universities offering teacher education programmes to reflect on also taking up outdoor project-based courses.

At universities, project-based learning becomes more and more common. Field trips or excursions are also common ingredients of study programs. In section 1, we presented the basic aspects to consider when planning project-based outdoor education: structure and alignment, assessment, situatedness, and equity issues. These aspects are not only relevant for outdoor education. They are foundational for all kinds of project-based learning, for organizing field trips and excursions. We believe that our detailed description and reflection of our course provides informative insights and knowledge not only for outdoor enthusiasts, but for all lecturers who want to complement their traditional in-class teaching.

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Appendix

Titles	Subjects	Description	Impression
To eat or not to eat	Biology	The students learn about edible and poisonous plants at various stations. They have to describe them and pick the edible plants to make a herb soup together. Formative assessment: the teacher shows certain plants and asks whether they should throw them into the cooking pot.	
Flight height of rockets	Physics, Chemistry	At various stations, the pupils test how high a water bottle with air pressure, a tablet tube with vinegar and baking powder and a tablet tube with cola and Mentos fly. First they predict which will fly highest. To measure the height, they receive various objects such as a meter rule and a protractor for triangulation.	
pH value and plants	Chemistry, Biology	Students explore how different conditions such as sunlight, soil and proximity to water affect the pH value, measure the pH value with a measuring device and categorize plants that grow there.	
Solar cooker	Biology, Geography, Chemistry	Students build different solar cookers to recognise the principles of reflection, absorption and heat trapping. All are set up at the same time and the temperature of the water is compared after a certain time.	

Water quality and machine learning	Informatics, Biology	Students look for creatures in the water which indicate the water quality. They identify them using an identification key. Then they send pictures of the identified creatures to the teacher. The teacher feeds the images to a machine learning model (e.g. Google Teachable Machine). After a certain time, they test the quality of the machine learning model for new images of such creatures.	
Navigation	Geography, Informatics	Students receive training at various stations information about navigation using maps, directions, or GPS, and have to find their way to the next station using the knowledge they have acquired. The stations use experiments and enquiry-based learning such as 'how many satellites do I need to identify the correct car from a row of lined-up cars?'	
Geo-Tagging	Geography, Biology, Informatics	Students divide into groups of 4 and these again into groups of 2. The groups of 2 look for various plants selected by the teacher at very specific locations and describe the plant and their locations as accurately as possible. They pass the descriptions to the other two group members, who have to find the plants. Points are awarded for each plant found.	
Catapult	Physics	Students build a catapult according to a manual. After that they think about optimizing the distance and accuracy of the catapult using physics principles and elaborate on the topic of oblique throw in a practical manner.	

Fire	Chemistry	Students divide into groups of 3 and try to light a fire with various tools as fast as possible without being explicitly instructed on how to do so. The task is structured as a group challenge. In the following various methods of how to light, burn and subsequently extinguish fire are covered in the outdoor unit.	
Micro:bit	Informatics, Biology	Using a micro computer 'micro:bit' students experience informatics in the outdoors: Different components and parts of the micro computer are visualized using materials stemming from the woods. In the following the micro:bit is used to simulate the spreading of a virus (Covid-19) and a metal detector is prepared to look for a lost ring.	
Pyrolysis cooker	Chemistry	Students build a pyrolysis cooker following simple instructions. The idea of the pyrolysis cooker is to burn the gases that are produced during pyrolysis, thereby achieving very high temperatures. To test the functionality of the cooker, it is filled with a minimal amount of wood, which must be sufficient to grill a sausage.	

Table A1: Selection of outdoor projects from our students.

A practical guide to integrating project-based learning into a curriculum to foster a competence-based learning environment

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Abstract

Project-based learning is an effective approach for developing subject-specific, method-specific, social, and personal competencies in university students. Development in higher education calls for integrating such courses into existing curricula. This might be challenging due to the lack of experience as well as time and knowledge constraints of the lecturers to design such courses. Yet, also integrating such courses into existing curricula can be challenging due to resource constraints. Therefore, we report on a practical guide for lecturers on how to design and implement a project-based learning environment that fosters subject-specific, method-specific, social and personal competencies. In the course Agro-Food Projects students of agricultural and food sciences at ETH Zurich work in teams to tackle practice-relevant, authentic, and complex challenges provided by a practice partner from the agri-food sector. The course follows a structured schedule with predefined deliverables and deadlines to promote self- and team-directed learning. Key elements for success include clear responsibilities among teaching staff, a well-organized schedule, and comprehensive support for students. Coaches play a crucial role in guiding the project teams while encouraging autonomy, ensuring that students engage actively with their projects. This course setting provides actionable strategies to encourage educators to implement effective project-based learning which fosters an environment where students take ownership of their learning journey.

Introduction

Practical experience, teamwork abilities, self-reliance, a sense of responsibility, communication skills, and intercultural, interpersonal and transferable competencies are often prioritized in hiring of university graduates, while subject specific knowledge is taken for granted (Heidenreich, 2016; Robertson-von Trotha, 2009). Graduates of ETH Zurich have excellent subject- and method-specific competencies though their transferable skills and practical experience could be strengthened (La Cara et al., 2023). This issue is also relevant for students in agricultural and food sciences (SVIAL, 2013). The importance of developing transferable competencies in graduates is crucial for these future professionals, as they are expected to be able to address complex local and global challenges.

This suggests that students should be trained beyond subject and method specific competencies to ensure their employability. Experience from higher and adult education shows that interpersonal and transferable competencies are often inadequately developed through standalone courses, as they usually lack aspects of direct application (Gotzen et al., 2012; Arbeitsstelle für Hochschuldidaktik, 2008). In contrast, project-based learning through practical and realistic tasks enhances both, the learning experience and the development of transferable competencies (Sá & Serpa, 2018; Nägele & Stalder, 2017). Addressing these gaps and

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improving the learning of transferable competencies has been a major focus of the AGROfutur degree programme initiative (Walter et al., 2015). Within this revision, the master's course Agro-Food Projects (formerly known as Interdisciplinary Project and, even earlier, Interdisziplinäre Arbeitswoche) was constantly adjusted to the needs of the current demand by the study programme. Throughout the lifetime of this course, an ongoing challenge has been the recruiting of a sufficient number of qualified lecturers, who participate as coaches in this course. This text will outline how these challenges have been addressed and mention the strategies that have been implemented to overcome them.

This project-based course has been a compulsory core component of the agricultural sciences curriculum for nearly thirty years. Since 2011, it has also been available as an elective for food science students (Elmiger, 2021). Since then, this hands-on, practice-oriented course has fostered the development and enhancement of both, subject-specific and transferable competencies. However, the teaching methods and learning content have evolved significantly over time, reflecting changes in higher education and changes in the degree programme. The course transitioned from a block week (Interdisziplinäre Arbeitswoche) during a lecture-free period after the end of the spring semester to a weekly class during the semester, supplemented by additional project days during the lecture-free period after spring semester. Most recently, its learning objectives have been aligned with the newly developed ETH Zurich Competence Framework (ETH Zurich, n.d.-a).

Within this context, our approach towards teaching and learning in this master's course is that students already have a set of experiences in transferable competencies from school, earlier semesters at ETH Zurich as well as from extracurricular activities. We can assume that they use these competencies and that they are capable of learning independently. Therefore, we can demand that students take responsibility for their own learning process and success. Thus, the lecturer's role is to provide the necessary framework and guidance for their self-directed learning by creating learning environments, such as project-based settings, in which students can actively develop, improve and test these competencies. To assist this process, lecturers provide learning material, guiding questions, opportunities for self-reflection, and peer interaction.

In the course Agro-Food Projects, students work in teams to tackle practice-relevant, authentic, and complex challenges provided by a practice partner from the agri-food sector. From our perspective, selecting practice partners with care is essential for successfully implementing this approach in any study programme and to ensure a meaningful and impactful learning experience for students. Practice partners are typically small and medium-sized enterprises, farm owners, or employees of agricultural education and advisory centres. The student teams are confronted with developing practical yet scientifically sound solutions that the practice partner can implement. Students learn to structure and manage a project in a self-organized manner, guiding it from the planning stage through to the results in the format of an oral presentation and written documentation that provide recommended actions for the practice partner. The course offers students a high degree of freedom and allows them, in collaboration with the practice partner, to define how they approach and solve the given challenge. Rather than relying solely on their existing knowledge, students need to transfer and adapt what they have previously learned to new situations to develop effective solutions, both individually and as a team. This often pushes students out of their comfort zones, as they encounter new and unfamiliar problems. Therefore, teaching staff of both study programmes is accompanying and guiding the student teams through the whole process.

Project-based courses typically involve substantial organizational effort, along with significant demands for financial resources and physical space. Additionally, they require skilled teaching staff who are properly trained and prepared for their supportive role (Dirsch-Weigand & Hampe, 2018). Looking ahead, we are likely to encounter constraints in terms of funding, available facilities, and personnel while student number increase steadily (ETH Zurich, n.d.-b). Despite these limitations, the need to incorporate active learning formats in higher education remains pressing and is one of the central principles of teaching at ETH Zurich (ETH Zurich, n.d.-c). Therefore, the challenge for the lecturer(s) in charge is to design interactive courses that promote sustainable learning and encourage students to be independent, self-motivated, and responsible for their own learning. How can such project-based courses be integrated into an existing or newly developed curriculum without placing excessive demands on resources such as personnel, financing and space? Furthermore, how can lecturers effectively implement project-based learning formats without the need to be experts in competence-based education or providing continuous feedback to every student or group of students?

In this report, we demonstrate how to integrate a project-based course into a curriculum even when faced with limited resources. We offer a practical guide for lecturers seeking to incorporate project-based learning into their teaching portfolios or study programmes in a straightforward and manageable way. Hence, we show that learning can occur anywhere, requiring minimal infrastructure, if the learning environment created supports learning.

A brief overview of the course programme

The master's course Agro-Food Projects runs for one semester, featuring weekly four-hour activity slots (either lectures, discussions or time during which students work on their projects). In addition, the course includes four consecutive project days, culminating in a final event held during the lecture-free period in the third week following the spring semester's end. Students are also encouraged to dedicate time outside of class to advance their projects.[2]

The course is designed around three main learning objectives (see https://vorlesungen.ethz.ch, select spring semester and course unit Agro-Food Projects/Praxisprojekte Agro-Food) and follows a structured schedule divided into specific phases with various learning activities, as shown in the advance organizer (Fig. 1). It includes lecture sessions that provide guidance on what to develop, how to approach it, as well as designated time slots for students to work on deliverables (milestones) and assignments that must be submitted on time. This sequential schedule of predefined deliverables and deadlines fosters commitment and ensures that student teams can complete their projects in time (Fig. 1). Such a structured timeline with fixed deadlines is strongly recommended for the development of self-directed learning environments (reviewed in e.g. Zeller Moser & Jenert, 2018).

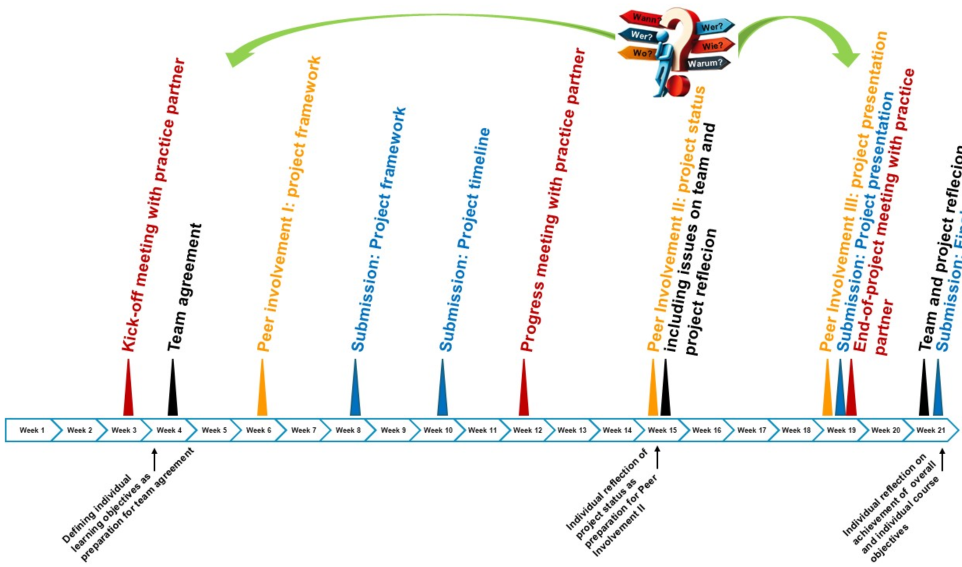

Figure 1: Advance Organizer of the course Agro-Food Project illustrating the course schedule with various tasks and deadlines of deliverables. Blue: deliverables; black: reflection points: orange: peer interaction sequences, red: meeting with practice partner. Additionally, the individual tasks to be submitted are shown on the bottom line, with the arrow indicating when they must be submitted. The figure on the top was prompted with DALL-E.

[2] Readers interested in receiving the detailed course schedule can address the authors of this article.

During the first lecture, students are introduced to the course and its requirements, before the assigned coaches present the available projects and the respective practice partners. Students then use a web application to select and rank their top half of projects by priority. The assignment of the students to one of their selected projects is performed by the core team. It tries to assign the students according to their highest priority, which is not always possible. This method diverges from the recommendation to optimize team diversity by intentionally forming teams with varied, complementary personality types e.g. Belbin[3]. Our approach usually results in project teams in which students work with colleagues they have not collaborated with before. Thus, this simulates a real-world work environment scenario, in which team compositions may not always be ideal. The optimal team size has been found to be four to six students per project. In spring term of 2024, 42 students participated in the course; but in principle the course is designed to scale and accommodate larger student numbers. The teaching staff, so-called coaches, are recruited from professorships teaching at both study programmes (in spring 2024, twenty coaches were involved). The important role of the coaches will be described in detail below.

After the second lecture, the student teams meet with their coaches to introduce each other and prepare for the kick-off project meeting with the practice partner, scheduled for the following week at the partner's location. After visiting the practice partner, students start working on their project by independently determining their approach according to the project questions or problems illustrated by the practice partner with guidance from their coaches.

At this point a challenge might be that students are not familiar with a project-based, active learning environment, because they typically experienced traditional lecture-based teaching and passive learning (reviewed in e.g. Zeller Moser & Jenert, 2018). Thus, students must shift from being passive recipients to active participants (Morrison, 2014), taking ownership of their learning rather than merely absorbing what the study programme provides. To address this important feature, we require students to set their own learning objectives for the course, thereby fostering their sense of responsibility and engagement for their educational journey.
Although the course encompasses elements of project management, teamwork, and transdisciplinary collaboration, these aspects have not been covered by theoretical lectures embedded in the course schedule for the past two years. This change was prompted by student feedback and significant resistance indicating that students did not find these instructions valuable at all to complete their project. Instead, we integrated questions related to these topics into the deliverables, requiring students to engage with and experience these elements implicitly through their work, since we consider them important. This approach has proven effective in prompting students to regularly reflect on these concepts through practical application.

Structured forms and guiding questions support the students to works on tasks and deliverables. In more detail, the following tasks and deliverables[4] are demanded from the students:

Four deliverables: These are required to be submitted at designated times, structuring the project process and guiding students through each step of the course. They are shown in blue in Figure 1.

1. *Project framework*: It ensures that the project work aligns with the assignment from the practice partner, creating a binding agreement for both the student project team and the practice partner.
2. *Project timeline:* It divides the entire project into smaller, manageable segments, allowing for effective planning and execution along the timeline.

[3] See here for more information: https://www.belbin.com
[4] Readers interested in receiving the guiding questions and forms can address the authors of this article.

3. *Project presentation:* It provides an opportunity to showcase their project work, by presenting the developed solutions, and delivering recommendations to the practice partner.
4. *Final report:* It provides an overview of the project's accomplishments and offers the practice partner a comprehensive foundation for implementing the insights and solutions developed by the students' project team.

Three peer-feedback sequences: The course emphasizes peer learning and feedback among groups. The arrangements for these sequences are indicated in orange in Figure 1. Two student teams support each other throughout the project, offering mutual feedback on each other's progress and results. This peer feedback process together with the input from the practice partner and the coaches enhances both the learning experience and the overall project outcome. It also helps students to improve their communication competencies and their ability to handle feedback, while promoting reflection on the project's progress within the teams.

- *Peer Involvement I*: Partner teams collaboratively review and discuss each other's project framework.
- *Peer Involvement II*: Each project team evaluates their current project status, analysing challenges in three key areas: team collaboration, team communication, and work organization. The team engages with the peer team to explore these issues and develop an action plan to ensure successful project completion. This sequence includes issues of team- and project reflection.
- *Peer Involvement III*: Practice and refine the project presentation in collaboration with the peer team and coaches, incorporating their feedback to improve the final delivery.

Three reflection points: The schedule and submission deadlines for the reflection points are indicated in black in Figure 1.

- *Defining individual learning objectives*: Students outline their individual subject-specific, method-specific, social, and personal learning objectives which they wish to achieve during the course. These objectives are regularly reviewed, assessed, and reflected throughout the course. They also serve as a foundation for the team agreement and the project reflection.
- *Team agreement*: In the team agreement, students of each team formalize a shared understanding on how they will collaborate with one another, the coaches, and the practice partner of the team. They establish agreed-upon guidelines for structuring their teamwork to achieve their subject-specific, method-specific, and social objectives.
- *Project reflection*: The project reflection serves as a retrospective for the student teams to review the entire project and to draw key lessons for future projects or their upcoming master's thesis. This reflection process includes evaluating their learning journey, project outcomes, team collaboration, interactions with coaches, and the transdisciplinary experience of working with a practice partner.

Key aspects for course success

For effective learning in project-based courses, clear and binding rules for students should be established (reviewed in e.g. Zeller et al., 2018). Within this framework, student teams are given the autonomy to self-organize. Three key elements have been identified which are crucial for the success of the course.

A. Clear responsibilities for the course: Core team and coaches

The teaching staff consists of the core team and the project assigned coaches, with core team members also partly serving as coaches. The core team holds overall responsibility for the course, which includes managing deliverables, ensuring their quality, and resolving any issues or conflicts within student teams, between students and coaches, or with practice partners. It may intervene in an advisory, mediating, or decisive action when necessary.

In the preparatory phase, the core team, in collaboration with coaches, selects appropriate practice partners and project ideas. Projects that offer students hands-on experience and opportunities to develop creative solutions are especially motivating.

Throughout the course, the core team provides lecture content. It organizes and moderates the starting and closing event. The core team also conducts a learning goal-oriented evaluation of the course. Additionally, the core team is responsible to check for the timely submission of student assignments, the final assessment of all student deliverables and assignments, as well as for performance assessments.

B. Well-organized course structure and clearly defined schedule

The course framework and performance assessment criteria are outlined in the course catalogue (see https://vorlesungen.ethz.ch, select spring semester and course unit Agro-Food Projects/Praxisprojekte Agro-Food). Moreover, the course schedule is explained in detail in the first lecture. Additionally, the binding submission deadlines as well as what is expected from the students, who participate in this course, is explained in detail at the beginning of the course. At the start of each input class, the advanced organizer (Fig. 1) is referenced to show students their current progress and what they are expected to do or elaborate during the upcoming weeks. Strict adherence to the schedule and deadlines is emphasized, ensuring that project teams remain on track (reviewed in Sukackė et al., 2022). All learning materials as well as the templates for deliverables and tasks are available in the corresponding Moodle course.

C. Well-defined framework and comprehensive student support

Given the wide variation in project topics, approaches, practice partners, and team constellations, three main learning objectives serve for the common understanding of the expected outcome of the course. Students are encouraged to actively contribute their knowledge and creativity to their projects, thereby taking ownership of their learning journey. They are responsible for driving their own learning success, managing the project work, as well as fostering the development of their peer team. Intrinsic motivation to participate in this project-based course is generally high, as students appreciate the opportunity for this unique hands-on learning experience.

Student teams are expected to proactively consult and coordinate with their coaches on plans and upcoming steps and are required to regularly update them on project progress and deliverable status. Feedback from coaches, and when necessary, the core team, must be discussed within the team and integrated into the project development.

To mitigate the risk of students disengaging in project-based learning, participation rules are clearly communicated and enforced. Additionally, challenges within the team, with practice partners, or with coaches, can negatively impact the learning experience. This risk is addressed by establishing a team agreement at the start of the course, providing team members a reference point for collaboration. Furthermore, the core team serves as mediator when conflicts arise.

Who are the coaches and what is their role?

Coaches are experienced teachers or doctoral students who already possess a high level of teaching skills. They are recruited across professorships of both degree programmes. As a result, minimal time, e.g. a two-hour workshop, is required to prepare them for their role in the course. The core team and coaches meet twice during the course to exchange insights into student teams and practice partners to mitigate any issues that could arise.

Each student team is assigned two coaches, ensuring continuity and coverage in case of scheduling conflicts. Many coaches commit to this role for several years. New coaches are preferably paired with experienced ones, who support them to learn their role. However, a potential challenge is the lack of suitable coaches to support the project-based course, particularly when no appropriate personnel are available within the professorships.

The major role of the coaches is to guide and support the student teams as a ‘guide on the side’ (King, 1993) throughout the learning process. Their role is to support, and, when necessary, steer the work and learning process of the student teams in the right direction. This is achieved through feedback and by initiating the student’s reflection processes, as suggested for example by Bachmann (2018) when creating learner-centred courses. Their supervision follows the principle of minimal assistance: ‘As little help as possible, as much help as necessary’ (Aebli, 2011). Furthermore, coaches monitor the quality of deliverables and provide suggestions for improvement (feedforward) on the final presentation, project work, teamwork, and final report. They can also intervene to mediate conflicts or involve the core team if needed.

How to find rooms and learning space

A single large plenary room is available that accommodates all students. However, it is not designed for team-based work. Unfortunately, there are no rooms nearby available where teams can collaborate, interact, and exchange ideas. To facilitate these productive interactions, we make use of the courtyard in the lecture building as a workspace (Fig. 2). Each team is provided with a bench set, presentation material, and a poster board. Coffee and cookies are offered. This setup has proven to be highly effective, creating a familiar and productive working environment that encourages collaboration within teams, across teams, and between teams and coaches. Thus, even without fully equipped rooms for project-based learning, other locations can be easily transformed to serve as an interactive working and learning space.

Figure 2: Student teams working in the courtyard of the LFW-building, a familiar and productive working atmosphere which facilitates intense collaboration and exchange within teams, among teams, and among the coaches of different teams. Photos by Brigitte Dorn, D-USYS.

How to create the ‘performance assessment’

Various forms of competence-oriented performance assessments are discussed, and rubrics have been proposed as a tool to help students prepare for these assessments (e.g. Zimmermann, 2018). However, the acquisition of transferable competencies is not ‘testable’ factual knowledge; it can only be assessed, if at all, in action-oriented situations or through a

developmental process in which students repeatedly engage with their competence acquisition (Arbeitsstelle für Hochschuldidaktik, 2008).
In group work, a key challenge is distinguishing individual contributions from the collective output of the team. Under these circumstances, an objective, precise, and reliably differentiating grading of the performance of individual team members is only possible with significant effort (Glathe & Schabel, 2014).

Due to the diversity of project topics, the individual and team performances are not comparable among the different project teams. Performance assessment is structured around a series of deliverables and tasks that require continuous engagement from students, both individually and as a team. It follows a 'pass' or 'fail' model. To pass, students must complete all tasks and deliverables and demonstrate active participation in the project work. Failure to do so, either through insufficient engagement or incomplete submission of required materials, may result in a failing grade. A good project result can only be achieved if students of a team cooperate. Students are required to work on the deliverables and tasks in a qualitatively appropriate manner. As stated in the course catalogue, attendance and active participation in the course are mandatory, and these requirements are enforced and checked by both the coaches and the core team.

Students in agricultural and food sciences have already acquired subject-specific and method-specific competencies during their bachelor's studies, such as scientific writing, presentation skills, and laboratory work. In the master's course Agro-Food Projects students must be able to adapt these competencies to the specific requirements of the project they are working on and the overarching learning objectives, following the instructions given during the course.

How can we identify whether the students have met the main learning objectives and reached their self-set learning objectives?

A. Main learning objectives

To assess whether students met both the course's main learning objectives of the course as well as their self-set learning objectives, a modified version of the learning goal-oriented evaluation (Frank et al., 2019) was conducted with participants from the spring semester of 2024. This method combines the results of quantitative and qualitative answers and prompts students to reflect on their learning, thereby identifying areas that were supportive for learning and areas where they faced challenges. Additionally, tailored evaluations, designed to suit the specific type and structure of a course, provide feedback by uncovering course weaknesses. This approach not only highlights areas for improvement but also serves as a form of feedforward, helping to enhance individual course quality, more effectively than the standardized course evaluations commonly used (Beywl et al., 2011; Frank et al., 2019).

Students rated their achievement of the three main learning objectives as well as their self-set subject-specific, method-based, social, and personal learning objectives by using a four-point Likert scale: a) fully achieved, b) partially achieved, c) rather not achieved, and d) not achieved. This four-point scale was intentionally chosen to avoid neutral responses to encourage a more decisive evaluation. To provide insights to the evaluation, students were also asked to explain their ratings.

Since completing the evaluation was compulsory for the performance assessment, forty out of 42 students participated (two students still needed to complete the evaluation). The results indicate that students generally met the main learning objectives of the course (Fig. 3), suggesting a good alignment between the course content, structure, and objectives. 72.5% of the students reported that they fully achieved the first learning objective of '*working in a team and developing scientifically sound, practical solutions to the questions posed by the practice partner*', while 27.5% reported at least partial achievement. For the second learning objective of '*preseningt the developed solutions in oral and written form in a comprehensible, convincing* *and appropriate manner*', 92.5% of students felt they had fully achieved this objective, while 7.5% reported partial success. Notably, for the third learning objective of '*reflecting on the work process and the project result individually, in the team, with the coaches and the practice partner and drawing conclusions for their actions in the current project and for future team and project work*', 87.5% of students felt they had fully achieved this goal, while only 12.5% indicated partial achievement. None of the students reported failing to achieve any of the three main learning objectives.

After the final project presentation, the student team, the coaches and the practice partner meet for mutual exchange and structured feedback on their project. This session is an essential element of the final event. Here, coaches and practice partners meet with the student team and comment on their performance. This feedback is highly appreciated by students, offering a far deeper appreciation than a numeric grade ever could. It is often during this session that students fully realize the impact of their work and its significance for everyone involved, in particular for the practice partner.

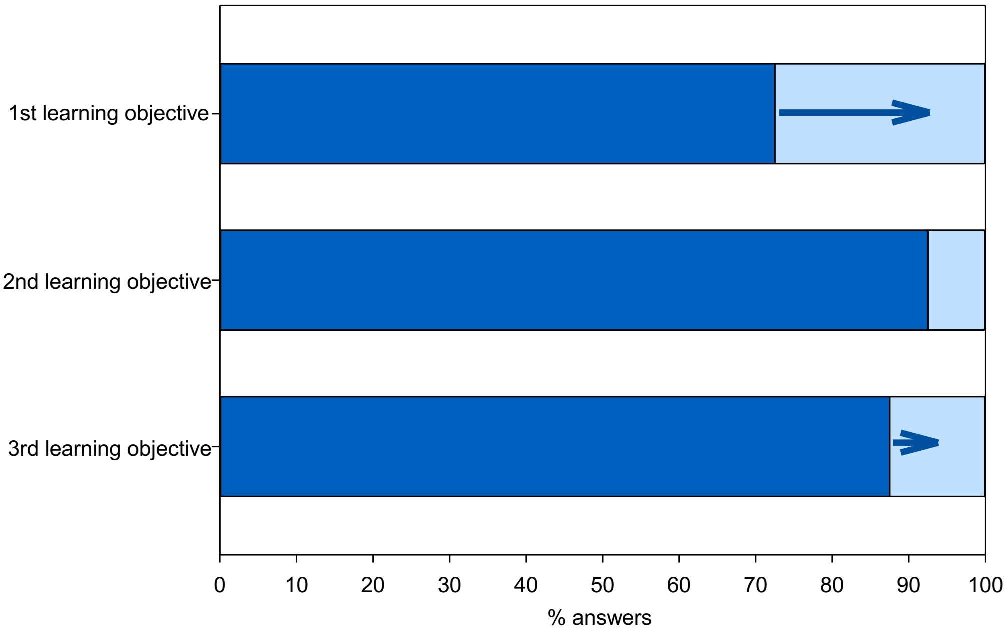

Figure 3: Achievement of the three main learning objectives in % of the answers. Arrow in the bar of the 1st learning objective indicates the eleven answers that could be moved towards 'fully achieved' indicating that all students achieved the first learning objective when analysing the text answers. Arrow in the bar with the 3rd learning objective indicates the four answers that could be moved towards 'fully achieved'. 4-point Likert scale (fully achieved, partially achieved, rather not achieved, not at all achieved), n = 40. Dark blue: fully achieved; light blue; partially achieved. None of the students answered with 'rather not achieved' or 'not at all achieved'.

However, what do these estimates really mean? To offer an insight into the student's perception of learning, we present three representative explanations from students who selected 'fully achieved'.:

- *Our question was completely different from what we learned at ETH, but we managed to find the solution as best we could through good research. But what was almost more important in our project was to apply the knowledge from our studies.*[5]
- *We were looking for solutions to a real problem. Several ideas were considered until we finally decided on the parameters we investigated. Although we were not able to definitely solve the problem, we were able to make a good suggestion.*[7]
- *I fully achieved this learning objective, as we developed and implemented the variety garden as a team, which can be used in teaching. It is therefore suitable for practical use and the fact sheets are scientifically sound.*[7,6]

[5] The original text was translated from German to English.
[6] For visual insights into one of the projects see (both last retrieved September 27, 2024):
   1. https://usys.ethz.ch/news-veranstaltungen/news/archiv/2024/07/getreidesorten-neu-entdeckt.html
   2. https://www.tiktok.com/@eth_dusys/video/7407334674030185761?lang=de-DE

An analysis of the students' written responses revealed that the few students who selected 'partially achieved' equally engaged in thorough and scientific work (see statements below). However, they evaluated their engagement more critically than their colleagues who chose 'fully achieved'. They were notably critical of the reliability of their solutions by citing insufficient data collection or insufficient literature or experimental data found to support firm conclusions for the practice partner. These eleven responses could be, in connection with the text analysis, classified as 'fully achieved', indicating that all students successfully met the first learning objective (blue arrow in Fig. 3).

- *We made a strong effort to develop a scientifically sound approach, but there were many limitations and compromises had to be made. Nevertheless, the results were presented in the right context and offer interesting insights despite the limitations.*[7]
- *We worked on a scientific question as a team and also successfully conducted an experiment, but the result has not yet generated a practical output.*[7]

Similarly, when analysing the text responses by 'partially achieved' of the third main learning objective, one student had completed the wrong answer, and the response was corrected to 'fully achieved'. The four remaining responses highlighted the value given of the peer feedback and reflection process, suggesting these students aligned more closely with 'fully achieved' rather than 'partially achieved' for the third learning objective (blue arrow in Fig. 3). The insight into their perspectives could be summarized as follows:

- *The back-and-forth exchange of ideas among all project participants was a very valuable method for receiving feedback and generating new ideas. This was especially important because our prior work on the different products often prevented us from taking on a fresh perspective – something that was sometimes necessary to fix even obvious mistakes.*[7]
- *I found the final discussion together with practice partners and coaches very useful to reflect on the project work again. However, I'm not sure how much I personally gained from all the assignments. I found it more draining than useful. I also found the first two peer involvements only moderately helpful. However, the third one, where we practiced the presentation together, was much more beneficial.*[7]

B. Self-set subject-specific, method-specific, social, and personal learning objectives

Students reported unanimously that they achieved their self-set subject-specific, method-specific, social, and personal learning objectives, indicating that the course fosters the learning of these important transferable competencies. 65.0% of the students claimed to have fully achieved the self-set subject-specific, 72.5% the method-specific, 75.0% the social, and 72.5% the personal learning objectives (Fig. 4). At first glance, these evaluations of the achievement of self-set learning objectives seems low. However, a deeper analysis of the text responses revealed that students again were highly self-critical in their evaluations of their achievements. Interestingly, 5% (2 out of 40) of the students indicated that they did not achieve their social learning objectives. One student mentioned ongoing difficulties with understanding and communicating in German, while the other expressed disappointment over not being able to engage as deeply with stakeholders as desired.

Therefore, it can be argued that students did, in fact, learn what the course aimed to promote: the improvement of important transferable competences such as teamwork, communication skills, critical thinking, problem solving and interpersonal skills by interacting with team members and practice partners. However, many were highly critical when evaluating their self-set learning objectives. This could suggest that students may not yet be familiar with defining their own learning objectives as well as to learn in competence-based and project-based courses.

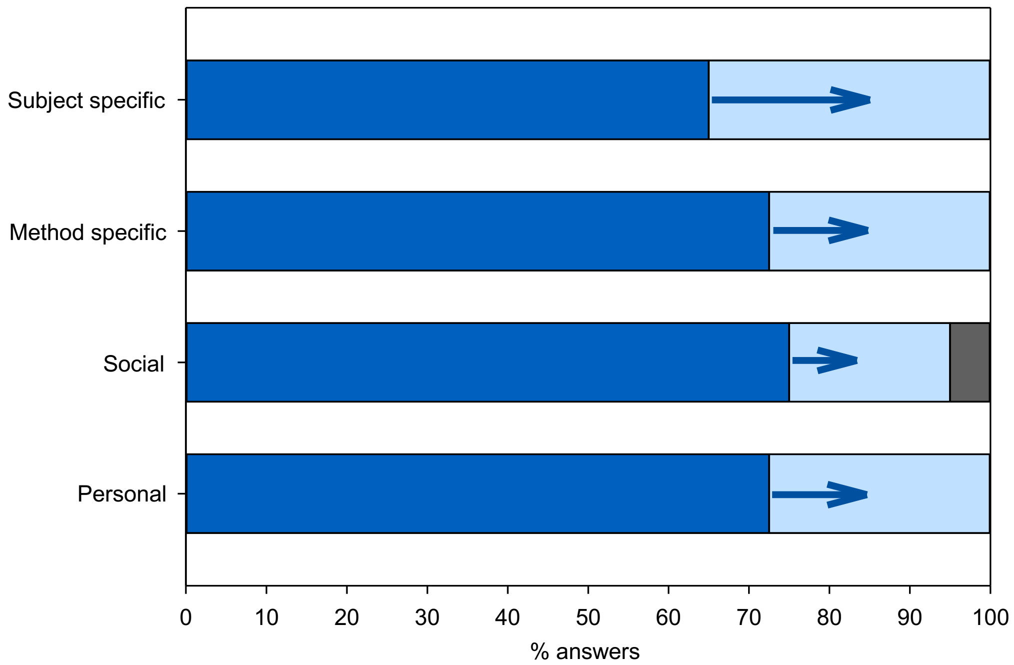

Figure 4: Achievement of the self-set subject-specific, method-specific, social and personal learning objectives in % of the answers. Arrow in each bar indicates that, including the text responses to the evaluation, would move the achievement rate towards higher answers for 'fully achieved'. 4-point Likert scale (fully achieved, partially achieved, rather not achieved, not at all achieved), n = 40. Dark blue: fully achieved; light blue; partially achieved; grey: 'rather not achieved'. None of the students answered with 'not at all achieved'.

Conclusion

This practical guide demonstrates how a project-based course can be effectively integrated into a curriculum, even with limited personnel, financial, and spatial resources. We also emphasize that these learning environments can remain simple, as effective learning in a project-based setting does not require complex infrastructure or an elaborate methodological framework. Furthermore, incorporating peer feedback, peer collaboration, and guided self and team reflection enhances critical thinking and fosters deeper learning. We suggest that a similar course outline could be easily adapted to other project-based learning environments in other study programmes wishing to incorporate project-based learning into their teaching portfolio or their study programmes in a straightforward and manageable manner. Nevertheless, guidance from experienced teaching staff is essential for success of project-based learning ultimately resulting in students taking ownership of their individual and team learning journeys. A potential challenge could be determining where to place a project-based course within the structure of a study programme. We recommend allocating at least one full afternoon for such a course. This would give student teams the flexibility to work on their projects, conduct experiments, travel to meet practice partners, or visit experts without time constraints. Our core insight over the years being responsible for this course is that a successful project-based learning environment relies on three key resources: engaged practice partners, a sufficient number of motivated coaches and a core team leading the course. Practice partners must be committed to collaborating with both coaches and students and offering a meaningful challenge for students to work on.

Or as students put it:

- *The course is very well organized and offers an incredibly great opportunity to work with a client in a very practical way. I was able to benefit from this course on various levels (professionally, methodologically, socially) and it also contributed a lot to my personal development.*[7]
- *Have faith in the process. In the beginning, it may seem like you will never reach a usable end product with your project work. But it can be compared to a small trickle of water that slowly makes its way and eventually develops into a river.*[7]

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Teaching architecture through an energy and climate lens

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Abstract

Despite the increasing societal awareness of the climate crisis, considerations of outdoor and indoor climate, energy consumption and generation, and the environmental impact of material choices still represent a niche in architectural practice. Given the urgency of the issue, addressing these topics needs to be integrated in architectural design. In this work, we first describe a build-up of teaching formats and position them in view of learners' competence development in architectural design through an energy and climate lens. We identify opportunities to refine our teaching instruments further and improve the learners' ability to independently integrate topics related to energy, emissions, climate, and comfort in the practice of design projects. We end with an outlook of an idealized build-up of these competencies across an architecture curriculum.

Introduction

In light of climate crisis and energy transition, sustainable building design, materialization, and energy use must be radically rethought. This necessary fundamental shift in how we retrofit existing and design new buildings requires a broad overview of the relevant factors and a deep understanding of their interrelationships and impact on architectural design. An integrated design process allows learners to understand the diverse interactions better and utilize them productively for design (Pelsmakers et al., 2022; Mumovic & Santamouris, 2013).

The Professorship of Architecture and Building Systems at ETH Zurich investigates how energy and climate-related building systems interact with architectural design. Figure 1 illustrates the multitude and complexity of energy and climate aspects with their corresponding building systems, which shape the conditions in architectural spaces to which building occupants are exposed. Integrated design involves studying the essential parameters and metrics related to the outdoor and indoor climate, local energy generation and consumption patterns, material choices, and their impact on the environment, e.g., visualized through Greenhouse Gas (GHG) emission timelines (Hischier et al., 2023), and the impact of design decisions on the building users, e.g., expressed by human comfort. An iterative process recognizes the interdependencies of design choices on different scales, therefore allowing architects to consider how new materials and approaches, energy demands, and infrastructure affect how we build.

Design studios are a prominent feature of architecture curricula. Despite a long tradition of blending the functional, structural, social, and technical, the integration of energy and climate perspectives in architectural design remains challenging. We have identified two gaps that hinder the application of energy and climate-related considerations in teaching architectural design:

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1. Theory classes on energy and climate are rarely directly related to the practical design work in design studios. As a result,
2. students find it difficult to effectively integrate energy and climate-related considerations when facing constraints and conflicting targets inherent to architectural design.

To help students develop expertise in integrated architectural design processes, we have gradually enriched all our energy and climate theory classes with project-based elements, such as group work on case studies and regular feedback sessions. With this contribution, we summarize achievements and challenges and give an outlook on how we intend to increase further the students' skills of integrating energy and climate into architectural design.

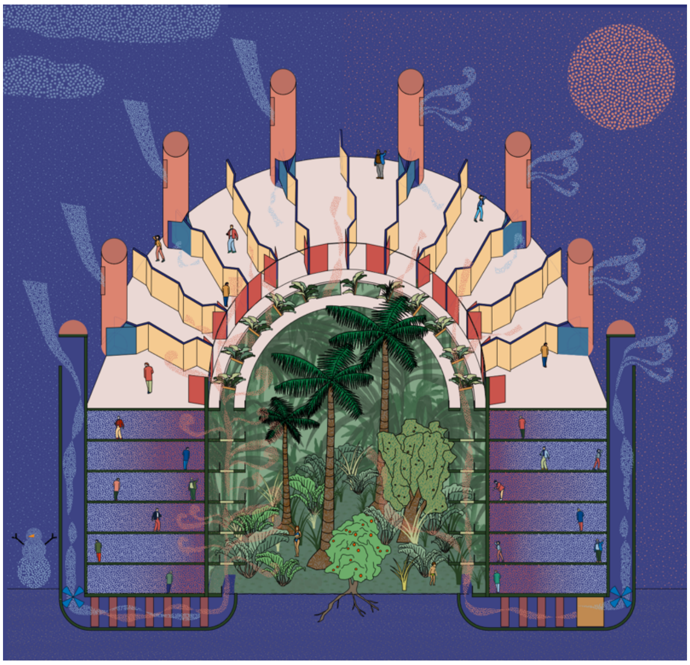

Figure 1: Integrated Design. An example from a collaborative design studio, where learners successfully integrated and visualized energy and climate topics in their projects (Schlueter & Bharathi, 2021).

Building competencies in energy and climate design across the architecture curriculum at ETH Zurich

Within the architecture curriculum at ETH Zurich, we have been building up a set of different project-based learning (PBL; Kuhn, 2001) formats over the last couple of years to support integrated design: *Energy and Climate Design* lectures, *Focus Work projects*, a *Building Integrated Photovoltaics Workshop*, *Computational Methods in Energy and Climate Design*, *Design Studio* projects, and the digital *Integrated Design Platform* for collaborative teaching and learning. Initially loosely connected, we gradually revised the different formats towards a stepladder approach where teaching and learning are aligned and build on each other. An overview of the learning goals, target level of learner independence for each course, and temporal embeddings of the courses in the curriculum are illustrated in Figure 2. The following sections summarize the individual formats and how we further developed and augmented the courses with PBL elements over the last few years. They lead to a proposal for a future revision, which is described in the latter part of this paper.

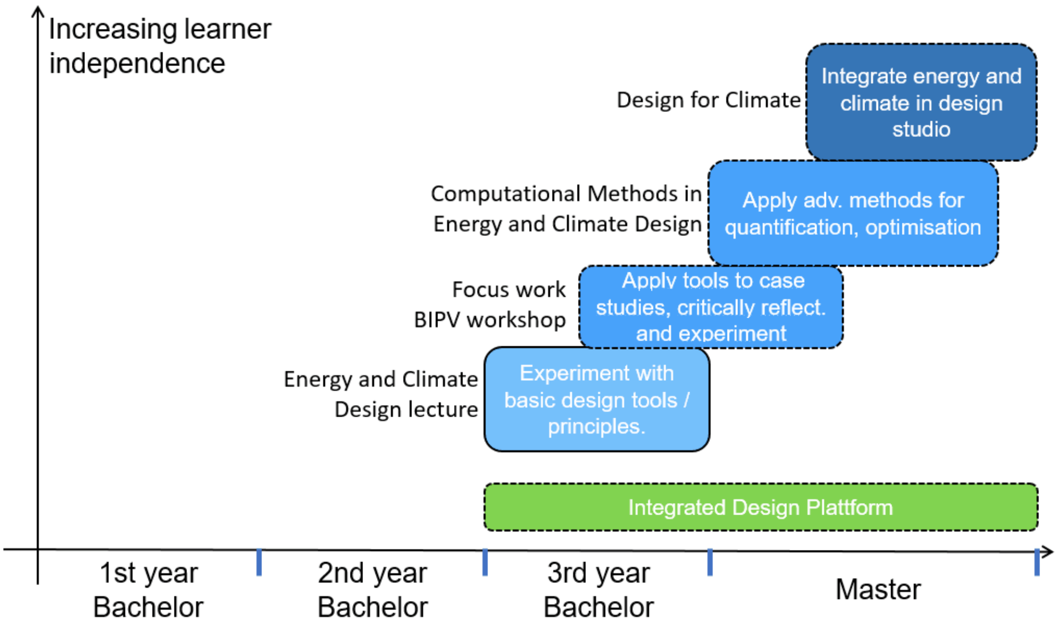

Figure 2: Overview of overarching learning goals and lecture formats in relation to the architecture curriculum (1st-3rd year Bachelor and Master classes) and level of learner independence.

Lecture: Energy and Climate Design 1 & 2

This course uses blended teaching to provide authentic practice opportunities and enable peer-to-peer learning. The two semesters were split into blocks of three weeks each. In each block, the 200-300 learners are given a set of tasks from a sub-topic, e.g., local climate and energy potentials, along with tool recommendations, case study examples, and minimal background information so that they can solve the tasks on their self-selected case study independently within a predetermined learner group. At the end of each block, each group received face-to-face feedback from a tutor (Figure 3, left).

Independent project: Focus Work

The project assists learners in transitioning from relying on teacher support to completing tasks independently. We use feedback and rubrics as ongoing, formative assessment methods to gather learner progress information (Yin et al., 2022). Learners receive feedback during mid-term and final presentations from peers and teachers. This ensures that learners receive regular, timely, and tailored support, helping them understand and integrate feedback effectively and enhancing their learning and performance.

Workshop: Building Integrated Photovoltaics (BIPV) Workshop

Learners designed and fabricated a physical Photovoltaics sample and explored its integration into architectural façades (Figure 3, right). The core concern addressed by this workshop was to accelerate design studio processes while retaining a project-based, hands-on learning experience in a 5-day block course. This was achieved through three measures:

1. Detailed step-by-step instructions guided learners through structured exercises.
2. Templates for submissions gave learners a rigid framework to minimize time spent on formatting and graphical representation.
3. A curated selection of buildings was provided for learners to choose from.

Lecture: Computational Methods in Energy and Climate Design

The course introduces computational design and analysis methods and tools for climate-responsive architectural design. Using a blended learning approach, learners receive targeted information through short input lectures and videos, allowing them to experiment with computational simulation tools. Class time is dedicated to active learning and discussions to synthesize the learned content of the course in exemplary architectural design tasks. A semester-long design assignment performed in groups encourages a project-based synthesis of content.

Design Studio: Design for Climate

This research-driven studio is offered in collaboration with two architectural design professorships from the Department of Architecture at ETH Zurich and their assistants. In addition, local practitioners from architecture and engineering joined the studio. Through inputs, exercises, and joint interdisciplinary supervision, the design studio assistants also acquire knowledge and methods from research, which they can apply to the supervision of other learners in their design studios. Learners were supervised in regular interdisciplinary desk reviews of researchers, experts, and designers.

Self-access toolbox: Integrated Design Platform

The platform supports autonomous learners in integrating energy and climate in architectural design. It intends to facilitate the exchange of knowledge and experience among learners, teachers, and researchers. It also serves as an interface for design studios led by other professorships that want to integrate climate and energy-related into their design assignments. The platform provides and recommends digital tools supporting integrated architectural design, a collection of case studies and stories reporting integrated architectural design, and opportunities to exchange knowledge.


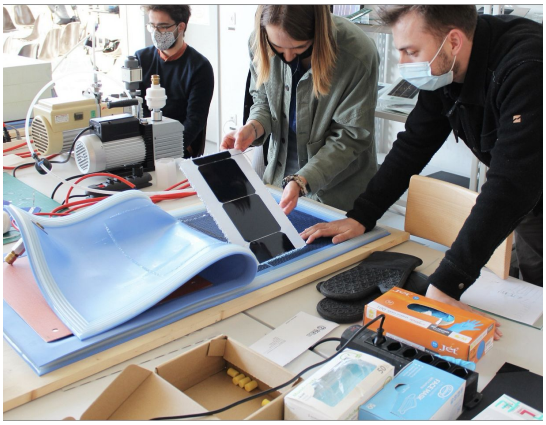

Figure 3: Left: Feedback in groups as part of blended teaching in Energy- and Climate Design. Right: Assembly of custom modules during the BIPV workshop.

Table 1 provides a concise overview of the learning opportunities offered to help students develop an integrated approach to energy and climate-inspired architectural design.

Course title	Type	Year	ECTS	Learning objectives / content
Energy- and Climate Design 1 & 2	mandatory	3rd year BSc	2 x 2	• experiment with basic tools and principles in energy and climate design. • develop a basic understanding of the interaction of passive and active building supply systems with architectural design.
Focus work project	mandatory	3rd year BSc and MA	6	• develop sustainable retrofit solutions. • make interconnections among various elements of sustainable building design. • work independently and make informed decisions. • encouraging reliance on judgment and feedback from peers and teachers.

Building Integrated Photovoltaics Workshop	elective	3rd year BSc and MA	2	• demystify the physics of solar energy production. • identify causal relationships between design decisions and technical outcomes.
Computational Methods of Energy- and Climate Design	elective	Master	3	• perform environmental site analysis for climate and (solar) energy potentials. • apply computational simulation tools to support performance-driven designs. • translate design ideas into parametric models and optimization problems.
Design for Climate	elective	3rd year BSc and Master	14	• utilize digital modeling, simulation, and toolsets to obtain quantitative data about design solutions. • merge quantitative data with design intent, spatial configuration, and spatial quality. • visualize integrated quantitative and qualitative results.
Integrated Design Platform	elective	Any	none	• provide support on requests for questions arising from architectural design.

Table 1: Overview of the stepladder approach to promoting energy and climate design perspectives in the Bachelor's curriculum in Architecture at ETH Zurich.

Discussion

Our interdisciplinary team has made the following observations about learners' competence development: we observed that learners who completed 'Energy and Climate Design 1 & 2' often encountered difficulties in selecting and applying appropriate skills and tools in subsequent architectural design studios. Many struggled with formulating basic questions concerning their design projects. However, learners who had taken additional courses, such as the 'Focus Project' or 'Computational Methods in Energy and Climate Design', were more effective in integrating energy- and climate-related considerations in their architectural designs.

Based on these observations, we identified three pathways to successfully translate energy and climate knowledge resulting from calculations and analyses into architectural design decisions:

1. Learners who take the full range of classes (mandatory and elective) *sufficiently train* the necessary skills to integrate energy and climate design in design classes.
2. Highly skilled and motivated learners reach a *high degree of autonomy*, i.e., they are able to successfully integrate energy and climate-related considerations in their architectural designs through self-study, when reaching out for targeted expert support through the 'Integrated Design Platform' (e.g., by booking consultations when needed).
3. A short intensive training on a focus topic (e.g., the BIPV workshop) establishes an *energy and climate lens* and positively influences learners' design decisions with quantitative analyses.

Summarising our experiences and observations, we propose integrating energy and climate design in the first year of the curriculum. This establishes the energy and climate lens early on as an integral perspective on architecture. In the ongoing revision of the bachelor curriculum, we are planning to select a single theme to illustrate collecting and framing relevant questions, selecting appropriate tools and experiments, performing analyses and interpreting results, integrating outcomes into design sketches and visualizations, and finally formulating new questions to inform project decisions further and refine the design with a view to energy and climate concerns.

Building on such an initial experience of integrating energy and climate as part of a design and using quantitative analyses to guide design decisions, we provide further opportunities environments in a lecture in the 2nd year of the Bachelor's Programme, a 'Focus Work' project in the 3rd year and the 'Integrated Design Platform' (see Figure 4) as ongoing support toolbox to help students independently integrate energy and climate design principles in architectural designs.

By shifting our focus from subjects to methodologies and positions and introducing an energy and climate lens and vocabulary early on, we hope that energy and climate become one of the foundational pillars for architectural education at ETH.

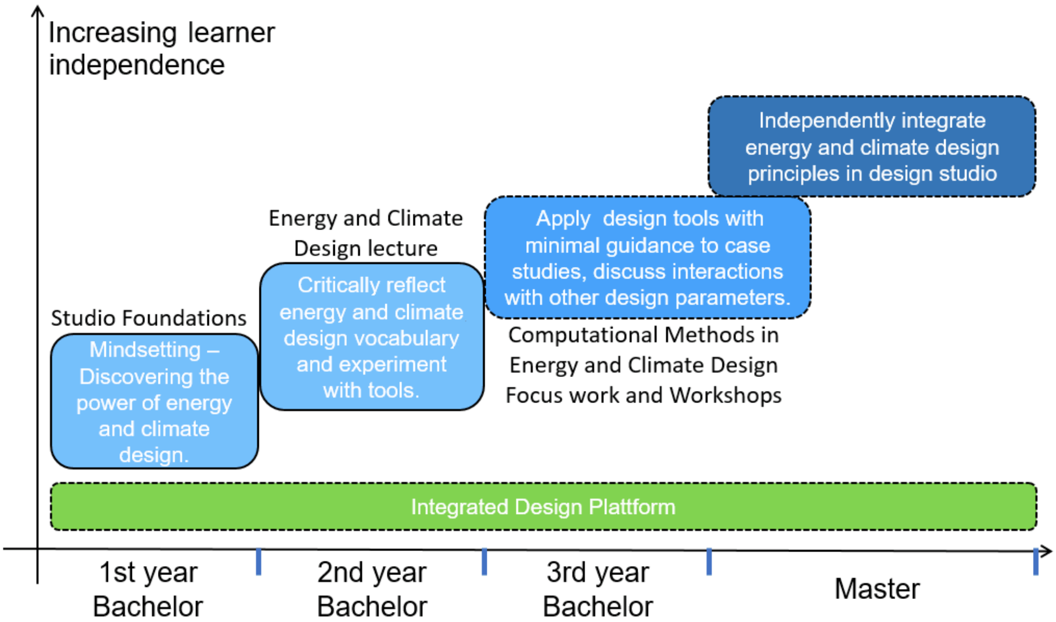

Figure 4: Proposal for a revised stepladder approach where an energy and climate lens and necessary vocabulary are established early, i.e., in the first Bachelor years, to inspire practice during the following design studio classes.

Conclusion

Translating energy and climate courses into PBL formats demonstrated that knowledge often considered 'too technical' and 'too theoretical' can be integrated into the architectural curriculum. However, the sporadic exposure to this topic within one course is insufficient to generally ensure informed decisions in design studios. Instead, continuous training throughout the curriculum needs to reinforce the learned competencies so that learners can translate them independently into solutions for new design problems. This motivated the planned revision of the curriculum, which shall equip all learners with a fundamental energy and climate lens that can be further developed and trained in later elective courses. Furthermore, enabling learners to seek targeted support fosters an autonomy crucial in developing design solutions and can be effectively addressed by platforms connecting peers and experts. When learned as integral aspects of architecture, we hope that energy and climate skills will translate the challenges imposed by climate change and energy transitions from complications into inspirations for future architectural design.

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Yes, we can: Empowering 21st century skills in a large introductory classroom through project-based learning

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Abstract

Fostering ‘21st Century Skills’ is becoming increasingly important in view of the rapidly changing world, with transferable competencies such as critical thinking, creativity, collaboration, and communication being crucial to succeed in work and society. Adapting university teaching to these requirements necessitates the development of appropriate curricula, courses, and teaching materials, as well as examinations that can adequately measure these competencies.

Various teaching methods are suited to convey transferable competencies, in particular student-centred methods like project-based learning (PBL), where learners work collaboratively on authentic problems. Many studies demonstrated that PBL improves understanding, team performance, motivation, and critical thinking, in contrast to conventional teaching formats where students are exposed to the material more passively with few opportunities to actively apply concepts and question them critically. The flipped classroom model can also contribute to fostering ‘21st Century Skills’ as shifting knowledge transfer to self-study creates space in courses for activities that train social and personal skills through discussions, group work, or PBL.

Promoting transferable skills is especially challenging in bachelor programs where courses are usually attended by many students with heterogeneous background knowledge, posing major challenges for lecture design. Thus, traditional, teacher-centred methods are often the format of choice. Here, we describe the development of a flipped classroom with a particular focus on project-based activities training social and personal skills for a large introductory biology lecture. By transferring part of the knowledge acquisition to the self-study phase, in-class sessions became free for project-based group work where students design experiments to study the genetic basis of diseases. At the end of the course, the groups present their projects in a poster session to their peers, the lecturers, and experts. Besides applying the knowledge acquired in the course, the group projects allow students to work on ‘real-world problems’ relevant to their field of study. Tutors (student teaching assistants) support students in their projects by providing feedback, clarifying questions, and evaluating the final project outcomes. The interdisciplinary nature of the project promotes problem-solving skills and critical thinking, while the didactic setting allows students to train their social competencies (cooperation & teamwork). Importantly, the group phase also impacts the skills development of the tutors, as they can expand their skills in the social and personal areas as well.

Implementing PBL to promote 21st Century Skills’ in large, heterogenous classes represents several challenges including infrastructural constraints, organizational complexity, and student motivation. This paper describes how a flipped classroom approach can support the development of competencies by PBL and suggests solutions to address challenges associated with this teaching format. Our analysis of student feedback collected over multiple years indicates that the project-based approach is effective in key aspects, such as group productivity, student-tutor interaction, and student motivation, and suggests that for certain student groups, fostering a stronger sense of project relatedness remains an area for future improvement.

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1. Introduction

1.1 What are 21st century skills?

In a fast-evolving work environment, personal and social skills are essential for individuals to effectively apply their specialized competencies at work and in society. These abilities, which are often referred to as transversal skills or '21st Century Skills', are traditionally summarized as the '4Cs' (critical thinking, creativity, collaboration, communication) and are more recently extended to include digital and technological literacy (Ananiadou & Claro, 2009). Although transversal skills are not a new concept of the 21st century, the term '21st Century Skills' is appropriate as it highlights the growing importance of these complex abilities in a world where rote memorization is declining, and cross-disciplinary skills are becoming more significant.

To ensure that graduates meet these requirements, university education must adapt. Implementing competency-based teaching requires developments at different levels. For example, '21st Century Skills' must be defined and organized into a coherent system (e.g., competency frameworks). Furthermore, curricula need to be developed or adapted to support the teaching of these skills, and suitable teaching strategies must be applied. Finally, assessments or evaluation frameworks should be developed to adequately measure and evaluate these complex skills (Geisinger, 2016).

Creating a detailed skills framework applicable for curriculum and course development requires identifying skills across cognitive, intrapersonal, interpersonal, and technical domains. In this context, it is important to differentiate between 'skills' (referring to practical abilities, e.g., technical skills) and 'competencies'. Competencies encompass a broad range of elements, including skills, attitudes, knowledge, and behaviour (Baartman & De Bruijn, 2011). While the term '21st Century Skills' might not fully capture the concept of competencies, it remains valuable for highlighting the increasing significance of complex abilities in a rapidly evolving world and the necessity of acquiring these competencies for success. Consequently, this article uses '21st Century Skills' and 'transversal skills/competencies' interchangeably.

1.2 How can 21st century skills be fostered in university settings?

Promoting transversal skills is gaining increasing importance in higher education. Surveys of companies and potential employers rate the technical skills of university graduates as very high, while transversal competencies are often less well developed (La Cara et al., 2023; Abela et al., 2020). This suggests that universities have not yet fully exploited their potential in developing transversal skills. Many universities are responding by implementing competency frameworks that serve as guides for both instructors and students in skills development. These systems help instructors to intentionally foster competencies and make the promotion of these skills visible to students. For students, competency frameworks are useful for reflecting on educational expectations and becoming aware of their own competency development (Baartman & De Bruijn, 2011).

At ETH Zurich, a key educational focus is on equipping students to become responsible, critical members of society. Thus, to raise awareness and promote holistic skill development with a particular focus on transversal skills, the ETH Competence Framework was developed. It includes 20 competencies in four areas (subject-specific, methodological, social, and personal competencies) and describes the knowledge, skills, and attitudes associated with each competency and serves as a common 'language' for instructors, students, and future employers (La Cara et al., 2023).

Applying competency frameworks to university study programmes requires the development of appropriate curricula, courses and teaching materials as well as examinations that can adequately promote and measure these competencies (Geisinger, 2016). Universities are challenged by the increasing demand for competency development and respond by creating course formats that foster these skills, leading to the establishment of standalone courses or projects designed to develop specific competencies (e.g., writing courses, interdisciplinary project work, etc.). However, the main challenge lies in adapting the existing curriculum to integrate the development of transversal skills within regular courses and established learning units. Several teaching methods are effective in training transversal skills, including student-centred approaches such as project-based education (PBE) or problem-based learning (PBL), where learners work collaboratively on real-world problems (Zhang L. & Ma Y., 2023; Wijnia et al., 2024). Both PBE and PBL emphasize group work, problem focus, and tutor guidance. Further, they both facilitate the application of knowledge to real-world contexts, increase motivation, engage students in complex tasks and foster self-directed learning and interpersonal skills. Additionally, they both share a commitment to interdisciplinarity, self-direction, and collaboration (Servant-Miklos, 2020). To differentiate between the two approaches, project-based education emphasizes the creation of a product as a solution to a problem that demonstrates student's understanding of the material. In contrast, problem-based learning prioritizes the process of acquiring new knowledge over the solution itself. Some argue that problem-based learning can be seen as a subset of project-based education, as solving defined problems is one of the methods used within project-based frameworks (Wijnia et al., 2024). Many studies have shown that project-based education can improve understanding, team performance, motivation and critical thinking in natural sciences and engineering curricula (Burks, 2022; Ralph, 2015; Kurt & Akoglu, 2023; Webster et al., 2022.; Zhang L. & Ma Y., 2023), while in conventional formats, students are exposed to the material more passively and have little opportunity to actively apply concepts and question them critically.

2. Project-based education in an introductory course with 350+ students

Although there is a growing demand to foster transversal skills in undergraduate programs, the reality in STEM disciplines often shows that traditional lecture-based formats remain the preferred choice, leaving little room for the development of '21st Century Skills.' Introductory courses are often attended by many students with diverse prior knowledge, which poses significant challenges on course design. However, many studies present ways to address these challenges by successfully implementing interactive formats (e.g., flipped classroom models, Deslauriers et al., 2011; Freeman, 2014) and demonstrating how these approaches can promote transversal skills (Väisänen & Hirsto, 2020).

Here, we describe the development and implementation of an introductory biology course based on a flipped classroom model that fosters transversal skills by learning through projects. By shifting the knowledge acquisition partly to self-study, we created space in the classroom for student-centred activities that train social (e.g., cooperation & teamwork) and personal skills (e.g., critical thinking) through project-based education. We also discuss the challenges associated with fostering transversal skills and present our approaches to tackling these challenges based on our learnings from seven years of implementing PBE. In summary, our approach illustrates how a project-based group phase helps Bachelor's students to tackle 'real-world interdisciplinary problems' that are relevant to their field of study with the help of course concepts in order to promote problem-solving skills, creative thinking, and collaboration.

2.1 Course structure and teaching activities

The course is an obligatory, first semester introductory biology lecture tailored to students studying health sciences and human medicine. It is composed of lectures, self-study modules, and project-based group work sessions (see Figure 1). The course is managed via the learning management system Moodle. During the asynchronous self-study phase, students primarily work individually on study materials specifically designed for the course (interactive lessons and quizzes). An online course forum is available for discussions. The knowledge gained through self-study is reinforced in the input lectures, which are supplemented with interactive elements such as clicker questions, think-pair-share activities, and concept mapping.

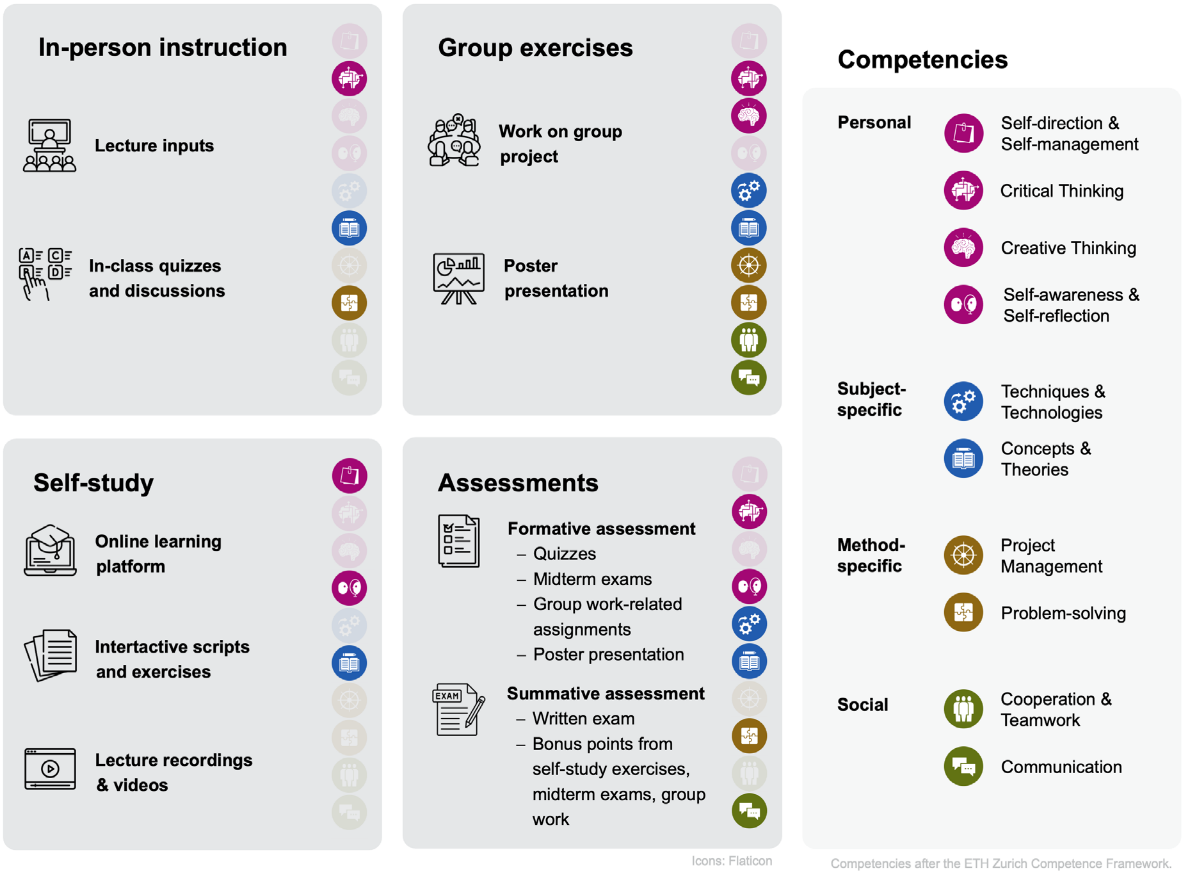

Figure 1: Overview of course activities and transversal competencies fostered. 50% of the lecture time is dedicated to in-person instruction, 30% to self-study, and 20% to tutored group project work. Several formative assessments during the semester are awarded with bonus points that can increase the final course grade. Competencies trained are highlighted (ETH Competence framework: Copyright: ETH Zurich).

In the project-based group phase, students work in teams of four on an experimental study to investigate the genetic basis underlying a disease, which they present as a poster in the last week of the semester (total number of teams on average: 90). While students can choose their teammates, the project (e.g., the disease) is allocated to each group for organizational matters (for example, to ensure that all projects are evenly distributed among the student teams). Besides applying the knowledge and techniques acquired in the course, the group projects allow students to work on 'real-world problems' relevant to their field of study. Through their work on the group project, students not only acquire method-specific competencies (e.g., problem-solving) but also social skills (collaboration & teamwork) and competencies in critical thinking, which is promoted by the interdisciplinary nature of the project. An overview over the group project phase is shown in Table 1.

Students from higher semesters act as tutors to coach the groups during their projects, meeting the groups every two weeks to discuss progress, clarify questions, provide feedback, and evaluate the final products and presentations. To exert their role, the tutors receive specific training and ongoing support throughout the semester from experienced tutors and a senior member of the teaching staff. The group phase also contributes to the competency development of the tutors, allowing them to strengthen their social skills like leadership and communication, as well as personal skills such as self-reflection.

Milestones in the group project phase	Contents and expected deliverables	Evaluation criteria
Group contract design	Group contract addressing the following aspects: - Communication (also in case of disagreement) - Distribution of work	- Completeness regarding the two main criteria - Timely submission - Confirmation by all group members
Literature review	Independent literature review on disease characteristics and molecular mechanisms of the disease	None.
Information gathering	Collaborative disease profile design focusing on: - Definition and clinical picture; onset of illness, life expectancy, and prevalence; therapeutic options - Disease inheritance; genetic basis and molecular disease mechanism	- Accuracy of the contents - Formal accuracy - Proper bibliography and appropriate reporting of AI usage
Peer feedback I	Mutual feedback within the groups on individual disease profile sections.	- Completeness of feedback (positive aspects and suggestions for improvement) - Constructiveness of feedback
Group work reflection I	Self-reflection feedback form to assess group work processes and personal learning outcomes; definition of a personal learning goal.	Marked as completed or incomplete. Anonymized results were discussed with the teaching assistants in the following exercise class to address potential problems.
Experimental design	Collaborative design of an experiment consisting of consecutive and logically connected steps to approach the previously reviewed disease.	Accuracy of the contents.
Peer feedback II	Between-group presentation and student-led feedback session on the preliminary elaboration of the experimental design.	None.
Poster preparation	Collaborative preparation of a poster combining information from the disease profile and the experimental design.	- Formal aspects: grammar, referencing, AI-usage, appropriate title choice, deadlines, and layout - Accuracy of the contents, described methods, and proposed next steps
Poster presentation and discussion	Student-led and teaching assistant-guided presentations of posters in a conference-like session.	Active participation through presenting, asking questions, and engaging in discussions.
Group work reflection II	Self-reflection feedback form to assess group collaboration (including possible intervention) and achievement of personal learning goals.	Marked as completed or incomplete.

Table 1: Overview of the group project phase.

2.2 Competency development in the group phase

The transversal competencies developed in the course are fully integrated into the subject-specific context, making their application and refinement more meaningful for the students. For example, during the group work, students deepen their understanding of the methods discussed in the course through the planning of an experiment, while simultaneously acquiring skills like problem-solving, critical thinking, and collaboration & teamwork, which are essential for their future work in a research group, in a hospital, or in industry (Figure 2).

The group project tasks are formulated to represent 'real-world scenarios' that students may encounter later in their career. For example, in one case, students are asked to step into the role of a Master student seeking a fellowship to pursue a doctoral study on a specific disease in a lab. The group's task is then to design an experimental study and present it at a conference in front of the fellowship committee to compete for the fellowship. The best poster presentations are then awarded with a price, symbolizing the fellowship.

The task of the group project is designed to foster problem-solving and critical thinking skills: by having to design an experimental study, students learn how to use resources and techniques to find possible solutions to a problem. By doing so, they need to evaluate different solutions and situations (e.g., experimental approaches) and choose the one they think is best suited to answer their research question. There is a specific emphasis in the group work on literature search and correct citations, including the use of AI, to train student's abilities to search for and critically select and synthesise information from different resources (lecture material, journal articles, books, AI) that might support their research question and inform their experimental study. Having to defend their work at the final poster session in front of peers and experts, students are trained in their ability to formulate own arguments, discuss alternative approaches, and anticipate the outcomes of their work (Figure 2).

While the task theme of experimental design primarily develops problem-solving and critical thinking skills, the didactic framework is designed to train social skills. Firstly, the project simulates not only real-world topics but also a realistic working framework. Just as in professional settings, the student groups must function effectively, which is supported by the creation of a group contract. This contract establishes guidelines for how the group will collaborate. As it is likely that students encounter challenging team dynamics now and later in their careers, the group work provides a learning environment to develop strategies for creating a positive team environment and managing team conflicts. To further support this goal, two short reflection activities are incorporated at different points during the group phase to encourage students to assess their group experience and learn how to improve it. Furthermore, peer feedback is built into the process, with students providing feedback to the members of their own group as well as on the work of other groups. These reflection and feedback activities aim at specifically fostering students' abilities to build relationships with others to work towards a common goal in a constructive atmosphere as well as to give and receive constructive feedback.

3. Challenges and (some) solutions to make PBE work with 350+ students

Despite the usefulness of PBE pedagogy, implementing project-based modules and managing the learning process remains challenging. We will discuss below the main challenges and present our solutions to some of them.

3.1 Infrastructural constraints

First, the teaching infrastructure at universities is often not adapted to the needs of group work activities, and suitable rooms for working in groups and presenting projects are missing, especially for large groups (e.g. several hundred students). Although many initiatives aim at providing space for project-based education – for example, dedicated maker spaces for students to perform projects or multifunctional rooms that can be used for both lectures and group work – these spaces can usually host only a limited number of students at a time. For large classes, however, group sizes should be kept small to ensure the maximal group experience to contrast the large lecture halls where an anonymous atmosphere prevails (Zhang L. & Ma Y., 2023). In the course presented here, the first editions of the project-based modules were held in the lecture halls, with up to 120 students and eight tutors working in parallel and various sequential tutoring sessions.

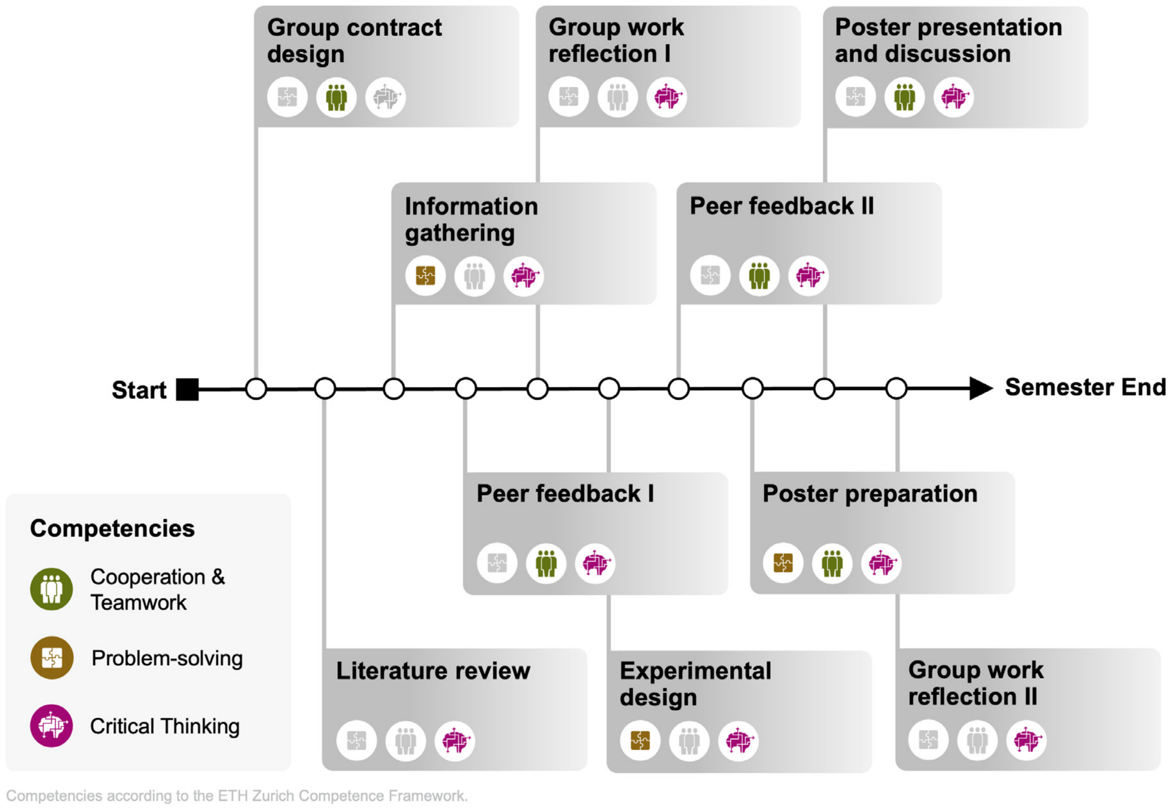

Figure 2: Training 21st Century Skills in the group project phase: important milestones. Competency development at the different milestones is described in the text (ETH Competence framework: Copyright: ETH Zurich).

Although this is possible, our experience clearly showed that separate rooms shared by 1 or 2 tutors are critical, as they greatly increased the quality of student-tutor and student-student interaction. Meanwhile, the group work sessions are held in seminar rooms, the number of which roughly equals the number of tutors involved. Universities will have to adapt their teaching infrastructure such that effective PBE will be possible with large groups, for instance, by transforming frontal lecture settings into smart classrooms, especially if project-based education is envisioned to be implemented for large classes and eventually, for many classes within various university curricula. ETH Zurich has recently started this process by building a dedicated facility for project-based education (PBLabs[2]) that offers flexible solutions for a variety of teaching settings for up to 120 students.

3.2 Management of the learning process

Besides infrastructural concerns, teachers adopting PBE may find it challenging to organize and oversee the learning process. This includes providing the learning materials, keeping up with students' personal and in-group collaboration progress, checking up on students' performance, providing timely feedback, and supporting sufficient interactions among students and teachers (Haatainen & Aksela, 2021). Hence, a solution that assists teachers in managing the mentioned efforts is highly desired. Especially for large classes, these efforts multiply dramatically, and consequently, one teacher cannot deal with PBE in a large class on his own but highly depends on co-teachers and/or assistants. In the teaching scenario we describe here, one lecturer took the lead for organizing and managing the group work. She is assisted by one or two senior teaching staff members and up to 25 student assistants (tutors) over the course of the group phase. The manager and the senior staff members are responsible for recruiting, training, and supervising of the tutors during the semester. The training includes a half-day workshop to convey didactic and organizational matters as well as several meetings during the semester to discuss the upcoming tasks, clarify questions and solve possible

[2] https://ethz.ch/en/the-eth-zurich/education/pblabs.html

problems. A ‘buddy’-system, where a ‘new’ tutor teams up with an experienced tutor, ensures best support for new teaching assistants, and a chat is available for immediate questions and help. The tutors themselves are responsible for organizing the meetings with their groups, discussing the groups’ progress, giving feedback on students’ work and assessing students’ performance during the entire group project phase. Each tutor spends between one and two hours per week with their groups. To perform their task, the tutors are provided with detailed documentation for the different steps of the group phase as well as on feedback and grading criteria to ensure that all tutors handle group management and evaluation in a comparable and fair way.

3.3 Student motivation

Problem-based methods can enhance motivation as centering learning around real-world problems is suggested to make learning more interesting and relevant for students. However, research has identified motivational challenges, including lack of participation or engagement (Winja, 2011; Winja et al., 2024). Thus, for students to fully engage with the project, it should be relevant to their study programme and future professions, aligned with the learning goals of the course, and spark their interest and their perceptions of meaningfulness. Thus, students’ perceptions of the task value are critical aspects for motivation. The perceived value of a task has been described by Eccles & Wigfield to contain four factors: (a) intrinsic or interest value, (b) attainment value, (c) utility value, and (d) cost (Eccles & Wigfield, 2020; Winja et al., 2024). In the course described here, we aimed to increase the intrinsic interest value by tightly coupling the project with the course learning goals. The project serves to deepen the concepts taught in the course, e.g., types of genetic variations, principles of inheritance, expression of molecular traits, and gene technological methods by applying the taught concepts to a real-world example (an inheritable disease) in health science and medicine. The latter might also increase the perception of utility value: the task’s usefulness for future goals such as excelling in academic or industrial research environments or in the public health sector.

As each task carries perceived costs (e.g., effort, time, anxiety), students tend to avoid tasks if the costs outweigh the benefits (Winja et al., 2024). Compared to attending lectures, where the invested time is clearly defined, students might have difficulties estimating the amount of time they need to invest in projects, thus, working on group projects might feel excessive if not rewarded otherwise. We therefore decided to award a bonus for the activities students solve during the semester apart from the in-class lectures. While these activities are generally ungraded (the final course grade is determined by a written exam), students can obtain bonus points for the successful completion of the exercises and the group project, which can contribute towards their final grade of the course. Although student can participate in the exam and receive grade 6 (highest grade) without any bonus points, over 90% of the students take part in the bonus system. The bonus point system not only motivates students to actively participate during the semester, but also provides regular feedback on students’ learning progress, a benefit, which students often point out in the course evaluations.

3.4 Assessing the competencies fostered by project-based education

One of the most significant difficulties in project-based education lies in assessing the fostered transversal competencies. Unlike the measurement of simpler constructs such as factual knowledge, assessments that measure complex competencies need to consider the interrelationships between the individual elements contained within these competencies (e.g., attitudes, behaviours, or ways of acting and thinking) and account for them in the design of questions and evaluation scales. Often, subject-specific knowledge must also be included in the assessment to reflect real-life requirements. Furthermore, assessing these complex constructs requires the design of tasks that immerse the examinees in such complex constructs. Education, therefore, faces significant challenges in developing assessments that can measure ‘21st Century Skills.’ While analytical skills can be evaluated with standard test items, such as well-designed multiple-choice questions, a truly comprehensive assessment of personal and interpersonal skills would go beyond multiple-choice tests and include measures that foster creativity, reveal learner's thought processes, and promote collaboration. How tasks should be designed to assess transversal skills, how these skills can be meaningfully evaluated and, especially, how such assessments can be scaled is not yet fully addressed in the current literature.

Given these challenges, we chose not to assess the transversal skills in a regular test. Instead, we included the group project in the above-described bonus point system to provide students with feedback on their competency development without interfering with the high-stakes nature of the course exam. While we do not directly assess the quality of the interactions between the students, the criteria applied to assess the group projects do consider aspects of collaborative and teamwork behaviour. Although many criteria focus on content correctness and the feasibility of the experimental design, some criteria are specifically aimed at evaluating transversal skills development. For example, collaboration & teamwork competencies are evaluated by allocating points for the quality of the group contract (e.g., does it clearly outline the students' expectations for collaboration?), the quality of peer feedback (e.g., was the feedback constructive and meaningful?) and the quality of the poster presentation session (presentations, questions, and discussions). Students receive feedback on their development of critical thinking skills by assessing the quality of their literature review, the originality of their experimental approach, the alternative solutions they anticipated, and the logical sequence of arguments during presentations. Thus, by allocating bonus points based on students' efforts in developing transversal skills, students receive feedback on both their individual and their team performance, allowing students to track their own competency development in this course.

4. Learnings from PBE: Results from student evaluations

Generally, the described course format is well-received by students and the course ranks among the top 10% courses in terms of course evaluation scores compared to other courses on this study level. Although theses centrally administered course evaluation forms do not address specific teaching formats, such as project-based education, students regularly leave comments about the course format in the evaluation form. While students highly appreciate the bonus point system, some remain sceptic about the group work, especially regarding the time investment and the perceived task value. To gain insights into aspects specific for the project-based education module in our course, we regularly collect student feedback anonymously on the course leaning platform. Here, we will discuss items from these questionnaires that directly relate to the project-based phase. The methods and a description of data analysis strategy is attached to appendix.

First, we were interested to understand what aspects are most important to students in the group project phase. Interestingly, although a few students have voiced they would like to be assessed on a more individual basis, individual grading had no great importance for the majority of students. This speaks in favour of our approach to weighting the individual assessment less heavily than the group assessment, although individual student assessments may allow students to better track and demonstrate their own competency development. However, the transparency of the grading was rated as being critical for almost 60% of the students, indicating that clear assessment criteria for transversal skills that are understood and applied equally by all evaluators are essential. Not surprisingly, the group working atmosphere was indicated as the most important aspect in group projects (Figure 3). In our approach, we take student's considerations about group work into account by emphasizing the importance of a group contract and encourage students to reflect on their working attitude as a group in the two self-reflection modules at the beginning and at the end of the course.

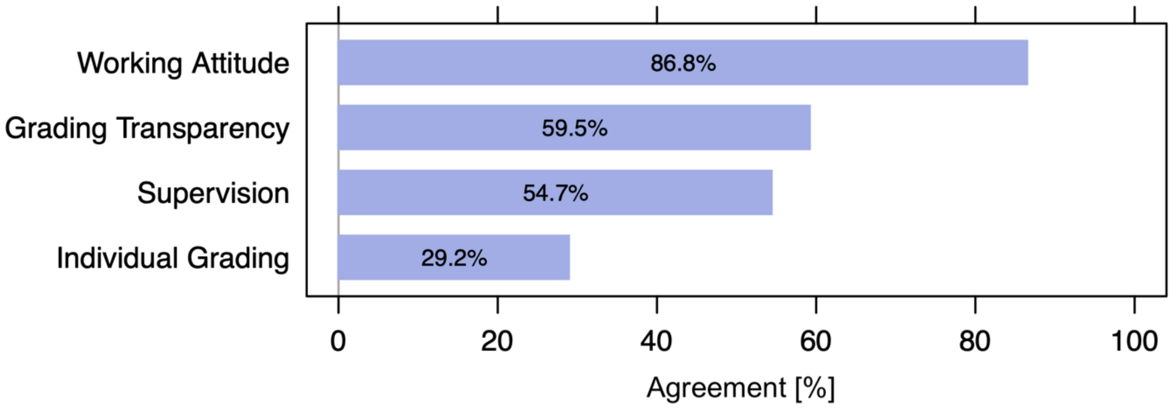

Figure 3: Aspects rated by students as being critical for working on group projects on a binary scale (yes / no). Results from anonymous feedback forms collected over several years (n = 1359, numbers are aggregated results from 5 consecutive years from 2017 to 2021).

Next, we gathered students' feedback on several aspects of the project phase, particularly regarding the effort invested and the effectiveness of the group work. Most students felt that their collaboration was productive (Figure 4, Table 2). However, students' perceptions on their investment into the group projects differed considerably, with nearly half of the students feeling that they had to acquire knowledge beyond what was described in the course objectives. This difference in perception may be linked to the heterogeneity of the group in terms of background knowledge and the time they invested in the task. Indeed, correlation analyses indicated a significant correlation between time spent on the project and the need to acquire additional knowledge ($r = 0.16$, $p < .05$). Students who reported spending more than 3 h per week on the project work were more likely to state that they had to gather a lot of additional knowledge. Given that project-based work often involves solving real-world problems, it is natural that students may need to go beyond the scope of the course. In future course iterations, it might be helpful to discuss this aspect with students to raise awareness.

The effectiveness of the project phase was investigated by asking students' perceptions on the relevance of the project work. Here, many students were uncertain about the extent to which the group project fostered their understanding of the course content (see Figure 4). Interestingly, students who felt that the group work was well suited to highlight the connections between the course topics also reported a greater benefit of the group work for deeper understanding of the course content ($r = 0.71$, $p < .0001$). Similarly, as stated above, the perceived relatedness of a project to the course goals might differ between student groups, depending on their prior knowledge, their interest in the topic, and the study programme they have enrolled in. Indeed, the perception of 'usefulness' differs significantly between students of the two study programmes, with medical students feeling less related to the topic of the group project (see Figure 5 and Table 3). As the group project focuses on experimental design, this might be less close to medical students whose prior goal is to become medical doctors. However, the rationale behind such experiments and the applied technologies are very relevant to medical doctors as they might encounter situations in which they need to consult patients about genetic diagnostic tools or decide on applying those. We therefore plan to provide slightly different frameworks for the group projects for both study groups by formulating some tasks more concretely around a story that represents an authentic situation for medical doctors (e.g., students are asked develop a technological pipeline to analyse patient samples in a clinical study or to defend their rationale for applying a certain technology in front of the board of head physicians in their hospital).

Category	*n*	Mean (± SD)	Median	Min	Max
Students' rating of critical aspects when working on group projects.					
Working attitude	1359	0.87 (0.34)	1	0	1
Grading transparency	1359	0.59 (0.49)	1	0	1
Supervision	1359	0.55 (0.50)	1	0	1
Individual grading	1359	0.29 (0.45)	0	0	1
Student feedback on students' investments and the effectiveness of the group work					
Our group collaboration was productive.	239	3.97 (1.20)	4	1	5
The group work was well−suited to highlight connections between the course topics.	239	2.95 (1.23)	3	1	5
To complete the group work tasks, I had to acquire a lot of knowledge beyond the course objectives.	239	2.88 (1.16)	3	1	5
The benefit of group work for deeper understanding of the course content was clear.	239	2.84 (1.28)	3	1	5
Student feedback on students' investments and the effectiveness of the group work by study major					
Health Science and Technology BSc					
Our group collaboration was productive.	169	3.99 (1.24)	4	1	5
The group work was well−suited to highlight connections between the course topics.	169	3.01 (1.23)	3	1	5
To complete the group work tasks, I had to acquire a lot of knowledge beyond the course objectives.	169	2.89 (1.15)	3	1	5
The benefit of group work for deeper understanding of the course content was clear.	169	2.99 (1.21)	3	1	5
Human medicine BSc				*1*	*5*
Our group collaboration was productive.	70	3.93 (1.12)	4	1	5
The group work was well−suited to highlight connections between the course topics.	70	2.83 (1.23)	3	1	5
To complete the group work tasks, I had to acquire a lot of knowledge beyond the course objectives.	70	2.87 (1.20)	3	1	5
The benefit of group work for deeper understanding of the course content was clear.	70	2.49 (1.38)	2	1	5
Student evaluation of the tutor's coaching competences					
Our tutor was always available for questions.	239	4.72 (0.67)	5	1	5
The group evaluations were plausible to me.	239	4.35 (0.91)	5	1	5
The tutor's feedback on our submissions was helpful and constructive.	239	4.31 (0.91)	5	1	5
Our tutor communicated the tasks clearly.	239	4.26 (0.96)	5	1	5
I received sufficient feedback during in−person sessions.	239	3.94 (1.23)	5	1	5

Table 2: Descriptive statistics of the reported data.

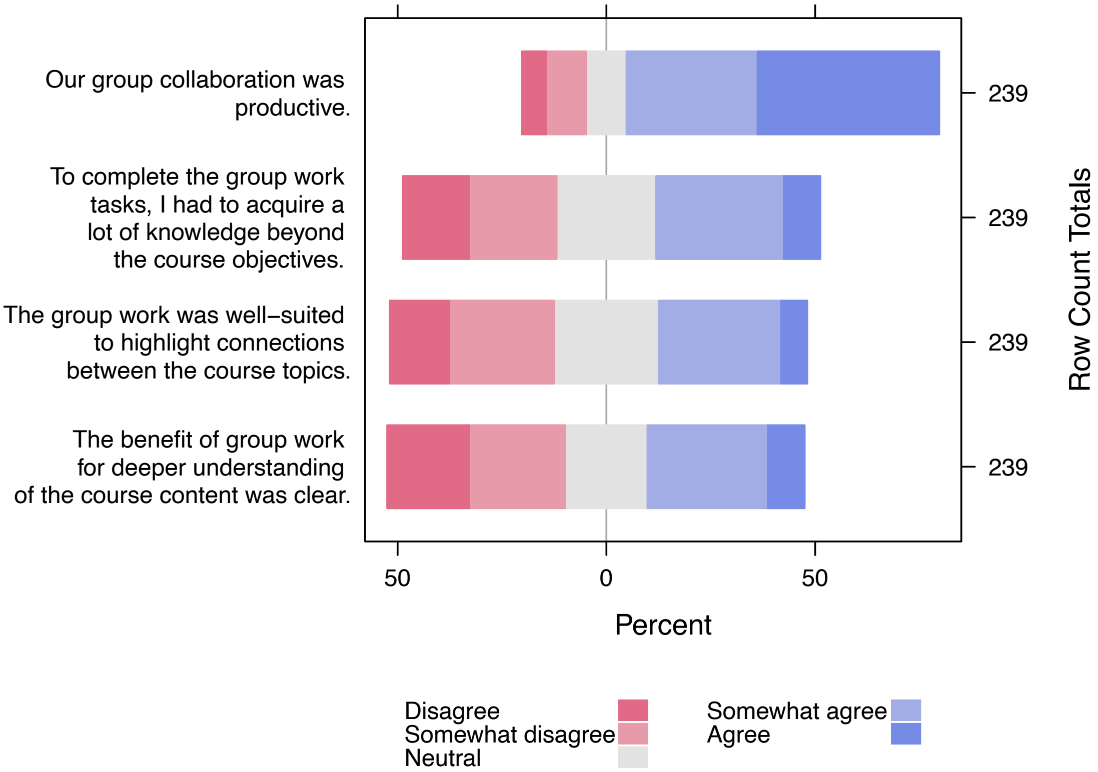

Figure 4: Student feedback on aspects related to students' investments and the effectiveness of the group work (answers provided on a 5-point Likert scale, data from the cohort of autumn semester 2023, n = 239). Descriptive statistics are shown in Table 2.

Finally, we also asked students for their feedback on the competences of the tutors. Students were very satisfied with the coaching performance regarding the tutor's openness to answer their questions, the explanations of the tasks, the feedback during the project phase and the final evaluation of their work. Some students would have liked to receive even more feedback from their coaches. In addition, many students left very positive comments on their individual tutors, indicating the quick response time of their tutor to their requests, their accommodating approach and patience, and their abilities to explain difficult content.

In summary, the evaluation results are promising, indicating that the project-based approach is effective in many aspects. Students appreciated interacting with the tutors and acknowledge the tutor's efforts in creating a pleasant and constructive working atmosphere. In line with this, the majority of students felt that their group work was productive. The evaluations also highlighted an area of improvement, as one student group expressed a lower sense of relatedness, encouraging us to further refine our approach of project-based education.

Category	n_{HST}	n_{MED}	**W-Statistic**	***p-Value***[1]	***r***
Our group collaboration was productive.	169	70	6321.5	1	0.06
The group work was well−suited to highlight connections between the course topics.	169	70	5967.5	1	0.01
To complete the group work tasks, I had to acquire a lot of knowledge beyond the course objectives.	169	70	6370.5	1	0.06
The benefit of group work for deeper understanding of the course content was clear.	169	70	7207.0	> .05	0.18

Table 3: Statistical analysis of group comparisons on students' investment and group work effectiveness r: Wilcoxon effect size; HST: Health Science and Technology BSc; MED: Human Medicine BSc. [1]p-value was Bonferroni-corrected for multiple testing.

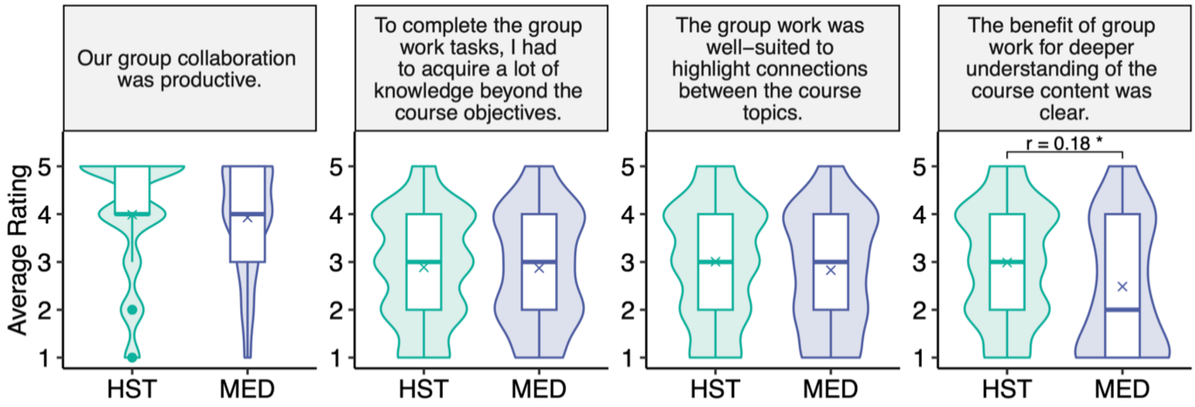

Figure 5: Student's perceptions on different aspects of the group project phase varies for students from different study programmes. Horizontal bars indicate medians, × indicates the group means, violin plots indicate the data density underlying the boxplot data, colored dots indicate single data points. Descriptive statistics are shown in Table 2, results from the statistical comparison in Table 3 (data from cohort of autumn semester 2023, n = 239).

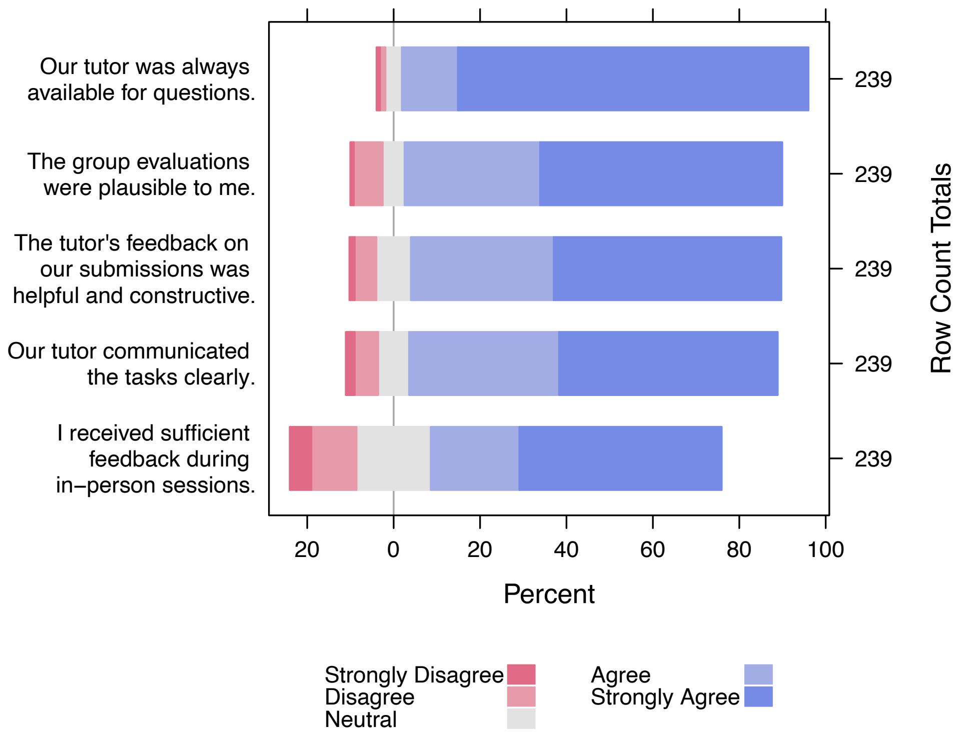

Figure 6: Student evaluation of the tutor's coaching competences. Descriptive statistics are shown in Table 2 (data from the cohort of autumn semester 2023, n = 239).

5. Implications for curriculum development

21st Century Skills are essential for effectively applying technical competencies in both the workplace and society. To meet these demands, university education must evolve by placing a greater emphasis on promoting such skills. Many universities are already aligning their educational programs towards these goals, offering various courses, workshops and opportunities to develop transversal competencies (e.g., KU Leuven[3], Columbia University, Princeton University). However, integrating transversal skill development into standard courses, which typically focus on methodological and disciplinary knowledge, remains a challenge.

[3] https://www.kuleuven.be/english/education/higher-education-advancement-fund/future-proof-programme-portfolio/Transversal-skills-for-the-21st-century

Teaching 21st Century Skills using project-based education has important implications for curriculum development, as it requires a fundamental shift from traditional content-based instruction (and examination) to a focus on skills like critical thinking, creativity, and collaboration. Thus, curricula need to incorporate objectives beyond subject mastery, emphasizing competencies that prepare students for real-world challenges. Since traditional exams do not measure 21st Century Skills effectively, frameworks for assessing students' development of complex skills, such as teamwork, need to be designed in order to align the curriculum goals with skill mastery.

The framework we propose in this paper demonstrates how project-based education can contribute to fostering methodological, social, and personal skills in a large, discipline-specific introductory course for first-year students. This model can inspire or enhance similar efforts in other courses and study programmes. Although certain challenges, such as infrastructural constraints, are more difficult to overcome, universities can support departments and institutes in developing project-based courses by enhancing educational support and creating lecturer or teaching staff positions, with the latter being critical to sustaining these initiatives on a longer term. Ultimately, these measures will facilitate shifting curriculum development towards providing students with opportunities to engage in meaningful projects that serve to develop skills needed in the modern world.

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Appendix

Methods

Participants

Survey data from 1598 first-semester students enrolled in two different study programs ('Health Science and Technology' and 'Human Medicine') at ETH Zürich, Switzerland, were combined in this study. Demographic data were not assessed. Participation in the surveys was voluntary; however, completing the questionnaires was one of several requirements to receive an additional end-of-semester bonus of 0.25 grade points on the final exam grade.

Questionnaires

The administered self-developed questionnaires addressed different aspects of group work as well as students' ratings of their teaching assistants. In the student cohorts from the autumn semesters of 2017 to 2021 (n = 1359), students were asked about critical aspects of group projects on a binary scale (yes/no) based on a predefined list of four items: working attitude, grading transparency, supervision, and individual grading. In the student cohort of the autumn semester 2023 (n = 239), responses were collected in more detail regarding students' investment in group work and their perceived effectiveness for personal learning gains. These responses were measured using a 5-point Likert scale questionnaire. To assess students' evaluations of their tutors' coaching competencies, an additional 5-point Likert scale questionnaire with five independent items was administered to the autumn 2023 cohort.

Data analysis

The questionnaire data regarding critical aspects of group work, students' investment in group work, and tutor evaluations were analyzed descriptively and visualized. Descriptive statistics are summarized in Table 2. Students' investment in group work and its perceived effectiveness in the autumn 2023 cohort were further analyzed by comparing ratings between the two study programs. To do so, a Wilcoxon Rank-Sum Test for independent samples with a non-normal data distribution was applied to investigate group differences between the two cohorts ('Health Science and Technology' and 'Human Medicine'). *p*-values were Bonferroni-corrected to adjust for multiple testing. The Wilcoxon effect size *r* was determined for each comparison using the following classifications: $0.1 \le r < 0.3$; medium: $0.3 \le r < 0.5$; large: $r \ge 0.5$.

Assessing transferable competencies in a real-world course setting with practice partners

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Abstract

Project-based education (PBE) has been increasingly adopted in various educational institutions to better prepare students for the complexities of the 'real world'. In this article, we present the course 'Applied Forest and Landscape Management Lab', highlighting its unique approach to project-based learning in collaboration with practice partners. In this course, students work in groups on a project such as developing a sustainable forest management plan in exchange with the cantonal authorities, local foresters and external experts. This experience enhances their understanding of theoretical concepts and prepares them for the challenges they may face in their future working environment.

In the course discussed in this article, student learning is assessed primarily through detailed written reports that are graded using rubrics that we revised to operationalise the ETH Competence Framework. Not all fostered competencies are well reflected in a written report, and we discuss other assessment forms such as oral presentations or peer feedback. While the project process is vital for learning, we concluded that for this course setting, grading only the final report aligns with real-world practices: students produce a comprehensive summary for the cantonal authority, similar to environmental consultants. This approach allows students to focus on creating a well-structured report and fosters an open environment for discussing group dynamics, cooperation, teamwork, and problem-solving with the supervising team, free from the stress of being graded on these aspects.

1. Introduction

Project-based education (PBE) has been widely adopted in higher education institutions because it effectively prepares students with the competencies needed to cope with the complexities of our modern world. At ETH Zurich, PBE has been strongly advocated through initiatives like PBLabs, which actively support and promote project-based learning throughout the institution (ETH Zurich, 2024a). PBE typically involves students working in teams on projects that address real-world challenges, thereby developing both subject-specific and transferable competencies. Core principles include integrating projects into the curriculum, situating them in real-world contexts, promoting student independence, and providing guidance through coaches and experts (ETH Zurich, 2024b).

In this article, we present the course 'Applied Forest and Landscape Management Lab'. A key aspect of the course is its emphasis on training students' subject-specific and transferable competencies (based on the ETH Competence Framework) in a real-world setting (La Cara et al., 2023a). Students work in small groups on a project in collaboration with cantonal authorities. This hands-on experience not only deepens their understanding of theoretical concepts but also equips them to handle the challenges they may encounter in their future careers.

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Overall, project-based courses are highly effective in fostering a wide range of competencies (Guo et al., 2020; Crespí et al., 2022). However, assessing and grading these diverse competencies can be challenging for lecturers. Currently, the course described in this article is assessed through detailed written reports. These are graded by the lecturers using specific rubrics that we have recently revised based on the ETH Competence Framework. In this article, we reflect on the experiences from revising the before mentioned rubrics to operationalise the ETH Competence Framework, the challenges of assessing transferable competencies, and discuss other forms of assessment such as oral presentations or peer feedback.

The course provides a playground to explore the following two questions:

1.) How can we operationalise the ETH Competence Framework using rubrics for a written report in PBE?
2.) What are the challenges in assessing transferable competencies with rubrics and what are alternative assessment formats in PBE?

2. Description of course setting

In the capstone course ‘Applied Forest and Landscape Management Lab’ of the Major Forest and Landscape Management (MSc Environmental Sciences), students take on the role of an environmental consulting office. Students work in groups of 2-7 people (usually 4-5) on projects that are of interest to the forest management or nature conservation authorities of a specific canton.

Course title	Applied Forest and Landscape Management Lab	**Course number**	701-1692-00L
Semester	spring semester, every year	**Credits**	5 CP
Typical number of students and staff	25 students 5 supervising teams 5 practice partners	**Hours**	5 days spread out during the semester, 2 block weeks after the semester on location / in the field
Offered in	Master’s in Environmental Sciences, Major Forest and Landscape Management		
Offered by	Institute of Terrestrial Ecosystems (ITES), Department of Environmental Systems Science (D-USYS), ETH Zurich		

Table 1: Course Overview.

2.1 Practice partners

A key aspect of this course is the practical work with cantonal authorities. We rotate our lab collaboration every 3-4 years. This approach ensures a continuous flow of relevant topics for the course that are up to date with current practice. As the course has been running for many years, we now have the comfortable situation that some staff members within these cantonal authorities have attended the course themselves during their studies and already know what to expect and how it is organised. This familiarity not only facilitates smoother collaboration but also enhances the learning experience for current students, as alumni can provide valuable insights and guidance based on their first-hand experience as course participants.

2.2 Search for project topics

The project topics are proposed by different employees of the canton, who then also act as the responsible client for the student group that chooses this topic. The project topics can range from agriculture or forestry-related questions to biodiversity or challenges related to natural hazards. Once the canton has sent their topic suggestions, we start the search for professors and lecturers within the Institute of Terrestrial Ecosystems (ITES) who could supervise the different topics according to their field of expertise. There is always a tandem of a professor or lecturer and an assistant or doctoral student who supervises the project from the ETH-side.

Although the topics are distributed according to the respective fields of expertise of the supervising team, the specific questions from the cantonal authorities within this field of expertise may not exactly match the specialisation of the supervising team. This requires a certain flexibility of the supervising team and at the same time, it requires the students to take ownership of their project.

2.3 Time frame

There are 5 days during the semester (mid-March to the end of May) which are reserved for working on the project, two weeks immediately after the end of the semester in the field, and one week of individual work (see Figure 1). The two weeks after the semester take place in the respective canton to facilitate field work and exchange with the cantonal authorities. The students have considerable freedom in organising themselves to deliver the defined project results. This leads to the first learning objective of the course:

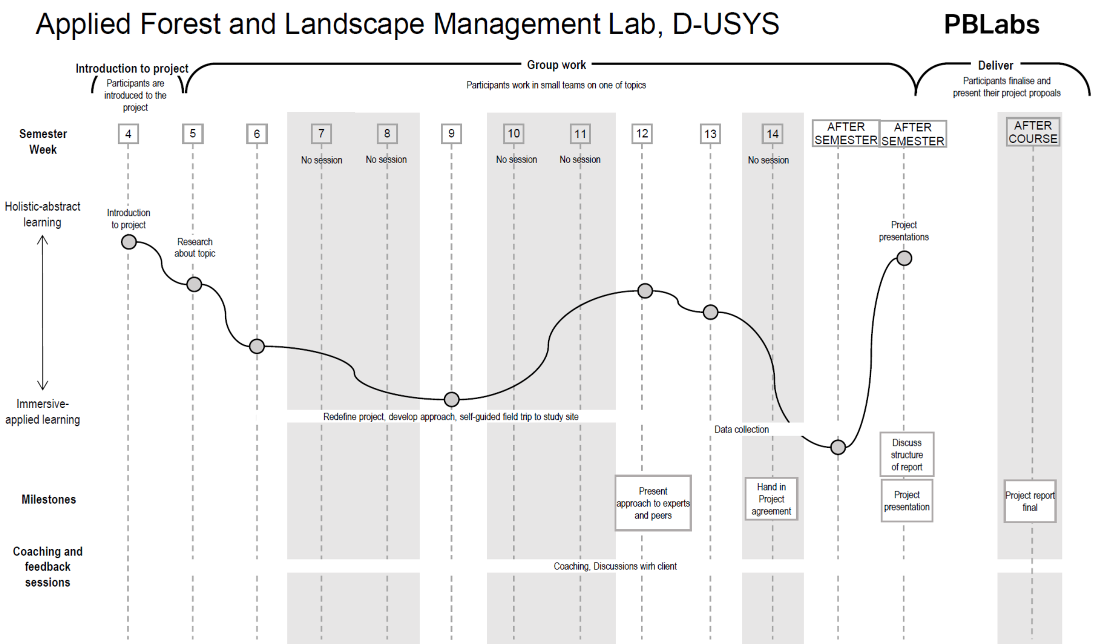

Figure 1: Action learning journey of the course 'Applied Forest and Landscape Management lab' (adapted Project-based education template of UTL).

2.4 Project definition

Before the students get to choose their project, a project description is developed in an iterative process between the lecturer team from ETH and the client from the cantonal authorities. The projects must require group discussion and have a 'think-tank' character. Cookbook projects are not suitable. The students will most likely have to adjust the initial research questions defined in the project description. This is the link to the second learning objective of this course:

- Learning objective 1: *Analyse, streamline and structure a real-world problem*

2.5 Project work

The student groups research, adapt and apply established methods to their project. Because the projects are so diverse, this process is different and unique for each group. Examples of methods applied include analysing spatial data using GIS, modelling habitat suitability, conducting fieldwork, or interviewing different stakeholders to collect data.

- Learning objective 2: *Adapt and apply known methods in a new context and deduct relevant suggestions for the client*

2.6 Presentation and report

On the last day of the two field weeks the students present their results to the cantonal authorities, the supervising teams from ETH and other interested partners. This is an opportunity to get some last feedback for the discussion and conclusion part of the report. The report must be handed in by the end of August and is graded by the supervising team from ETH.

- Learning objective 3: *Write a complete, concise and comprehensible report for your client following scientific requirements*

2.7 In the context of practice

As introduced before, this course emphasizes the real-world setting and lets students step into the role of an environmental consulting office. Aspects that differ from standard educational exercise are especially the following:

- The questions that need to be answered are co-created and redefined together with the client.
- The projects are of direct interest to the client and are used for the further development of projects and strategies.
- Students are responsible for project management and have to coordinate and communicate with their supervising team from ETH, their client and other relevant stakeholders from practice.

Compared to the role in an environmental consulting office, the only missing component is the acquisition process. Students do not have to write an offer to win the project, but they do have to specify what they can deliver within the time frame of this course. From experience, we can say that students usually overestimate what can be achieved in four working weeks. Most of the readers here can probably confirm that time estimations for projects are a very important, but also a lifelong learning process.

- Learning objective 4: *Deliver defined project results within the given time frame and appropriate communication with clients and other relevant partner*

For the client, currently the Canton of Zug, this course is an opportunity to ask questions that they are interested in but do not get a chance to address because other tasks are more urgent. This includes for example researching the effects of new forest management methods, how to cope with future challenges brought by climate change, or how to improve habitat suitability for rare species. The results from this course provide new inputs for the staff members of the cantonal authorities (Brüggemann et al., 2024). Inputs from past courses included implementation approaches and challenges of ecological infrastructure, analysis of forest inventories and management suggestions derived from this analysis, management suggestions to improve habitat suitability and connectivity for bats, new approaches for the cantonal forest development plan or the development of a concept for the renaturation of a landfill.

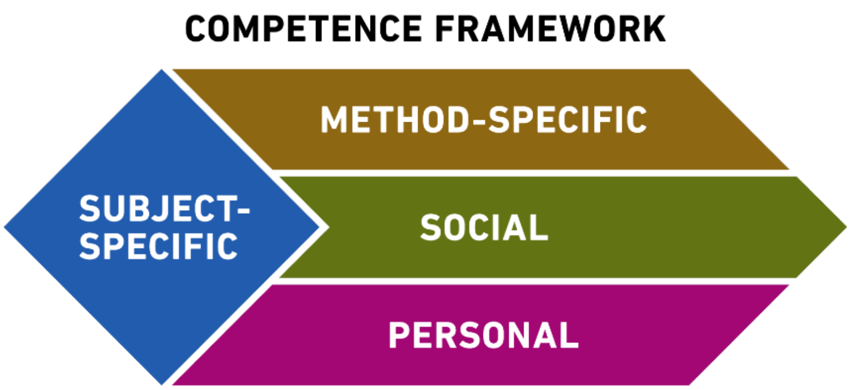

Figure 2: ETH Competence Framework. Copyright of ETH Zurich (ETH Zurich, 2024c). Full framework accessible via ETH Website: https://ethz.ch/en/the-eth-zurich/education/policy/eth-competencies-teaching.html

3. Operationalising the ETH Competence Framework in project-based courses using rubrics

The course has been running successfully for many years, consistently providing valuable practical experience to students. To further enhance its effectiveness and to align the course more closely with the latest educational developments at ETH, we decided to explicitly integrate the ETH Competence Framework (La Cara et al., 2023a), see Figure 2. We adapted the rubrics of the report evaluation and applied the ETH Competence Framework through discussion with experts from different fields (see acknowledgments).

The learning objectives are described in the course setting section (Chapter 2) of this article and form the basis for the report assessment rubrics (see Appendix, Figure A2). We developed them according to the main steps within the course, which need to be completed to deliver a successful result. To each learning objective, we assigned one or a maximum of two key competencies from the ETH Competence Framework which will be visible in the course catalogue (La Cara et al., 2023b). To achieve the reduction of all the competencies assessed to a maximum of three to five competencies 'assessed' for the course catalogue, we defined a hierarchy of the ETH Competence Framework specific to this course. The hierarchy is given by:

1. the learning objectives 1-4, which define the key competencies (marked as 'assessed' in the course catalogue)
2. the subcriteria needed to fulfil the learning objectives, that may include additional competencies

For the subcriteria, we developed text rubrics to grade the reports. The report assessment rubrics we developed are structured as follows (for detailed text assessment rubrics see Appendix):

- Learning objective 1: Analyse, streamline and structure a real-world project
  Key competence: Analytical competence
  - Define the project with a focus on the interest of the cantonal authorities
    Competencies: Problem-solving, Customer Orientation
  - Identify and formulate answerable goals and research questions.
    Competence: Analytical competence

- Learning objective 2: Adapt and apply known methods in a new context and deduct relevant suggestions for the client
  Key competence: Problem-solving
  - Question and adapt known ideas or methods
    Competencies: Subject-specific competencies, Creative Thinking, Critical Thinking
  - Make necessary assumptions: 1) where data is missing or not obtainable, 2) for comparison, 3) to define system boundaries
    Competence: Analytical competence
  - Deduct suggestions/recommendations including advantages, disadvantages and limitations
    Competence: Problem-solving
  - Describe limitations of project results
    Competence: Critical Thinking

- Learning objective 3: Write a complete, concise and comprehensible report for the client following scientific requirements
  Key competencies: Subject-specific competencies, Communication
  - Structure of report
    Competence: Subject-specific competencies, Communication
  - Quality of report parts
    Competencies: Subject-specific competencies, Analytical competencies, Decision-making, Problem solving
  - Formal quality of the report
    Competence: not applicable

- Learning objective 4: Deliver defined project results within the given time frame and appropriate communication with clients and other relevant partners
  Key competence: Project Management
  - Work independently and creatively (e.g. prepare and bring own ideas / suggestions to meetings)
    Competencies: Creative Thinking, Self-direction and Self-management
  - Plan and organize your project
    Competence: Project management
  - Communicate actively with coaches, experts, cantonal authorities and external experts
    Competence: Communication

Only the written report is graded and counts as a summative assessment; for the other learning objectives, students receive formative feedback during meetings with their supervising team and in discussions following the oral presentation.

However, we argue that especially in project-based learning, many more competencies are assessed (directly and/or indirectly) and even more are fostered. In the context of this course, this is supported by the subcriteria of the defined learning objective. In addition, some competencies are not directly assessed by the report assessment rubrics but are still fostered in the course:

- *Media and Digital Technology:* Students need to research literature as well as data and often use AI to get ahead in their projects. Some basic data is available, but most data has to be acquired by the students and is not pre-processed.
- *Cooperation and Teamwork:* Students work in groups of 2-7 people (usually 4-5) and need to organise themselves.
- *Sensitivity to Diversity:* Students need to interact with different stakeholders which they need to approach appropriately to successfully work with them.
- *Negotiation:* Students need to negotiate with different stakeholders and find solutions that are not necessarily the most efficient in a scientific sense, but that are applicable to the situation at hand.
- *Adaptability and Flexibility:* The basic idea of the project is given but needs to be adjusted based on the preparation and exchange with stakeholders.
- *Self-awareness and Self-reflection:* This is only implicitly fostered. The group must divide tasks within the project themselves. Well-performing groups are likely to have distributed tasks according to the strengths and weaknesses of individuals.

The ETH Competence Framework is divided into 20 different competencies (see Figure A1 in Appendix), from which 17 are assessed or fostered in this course (marked in yellow).

4. Challenges and alternative assessment formats for PBE

A particular challenge for the revision of the report assessment rubrics was the overlap between the different criteria assessed. One example is the adaptation and application of methods (learning objective 2) and the description of these in the report (learning objective 3). Although the application of methods and their documentation are distinct aspects, distinguishing between them for report assessment is not straightforward. While from a theoretical point of view, the application and the description of methods used are two separate things, in practice, they often are difficult to detangle because the understanding and the detail of the application of the methods by the student group are also reflected in the description thereof. For a thorough assessment, the supervising team has to be aware of possible overlaps and try to disentangle as much as possible to give the appropriate feedback.

Overall, relying solely on a graded final written report may be too limiting for appropriately assessing students' competencies in project-based courses. Exploring alternative assessment formats can provide a more holistic evaluation of students' competency development.

One alternative is grading intermediate steps of the project, such as through learning diaries, status meetings, or project management documentation. This approach allows competencies to be assessed on a finer scale, and the grade reflects not only the final product (i.e., summative assessment) but also the process (i.e., formative assessment). However, the intermediary steps may not be discussed as openly with the supervising teams if they are graded, preventing students from asking questions, receiving support, and constructive feedback (UZH, 2024). Additionally, this method requires more resources from the supervising team (Preiss et al., 2023).

Another option is grading the oral presentation. Presenting the project to the cantonal authorities provides practice for real-world situations and is resource-efficient for project partners and the supervising team. The current ungraded format allows for open discussion and feedback from cantonal authorities and the supervising team to be incorporated into the final report. Like grading the intermediate steps, we think that grading the oral presentation would put more pressure on students and prevent these fruitful, open discussions. For example, we encourage students to present critical points of their work to get input from cantonal authorities, lecturers and their peers.

Overall, while the process of working on the project is crucial for learning, it makes sense from a 'real-world perspective' to grade only the final report. This approach ensures that students focus on producing a comprehensive and well-structured report that summarises their findings for the cantonal authority in a concise manner, as they would do if they were working as environmental consultants for a canton. Since the group's journey through the project is so important, it is essential to create an environment where students can openly discuss group dynamics, cooperation, teamwork, and problem-solving strategies with their supervising team without the added stress of being graded on these aspects.

To further enhance the learning experience in future iterations of the course, incorporating a peer assessment component could be beneficial. This method would allow students to evaluate each other's contributions, thereby emphasising the importance of social competencies such as communication, cooperation, and teamwork, as well as personal competencies like self and group reflection (Topping, 2017). However, it requires even more resources from students in an already intense course setting and needs to be carefully designed and introduced by the supervising team.

5. Reflections and outlook

We revised the report assessment rubrics for the ‘Applied Forest and Landscape Management Lab’ through an iterative process to clearly define the primary learning objectives and main competencies. By focusing on these competencies, the course provides a transparent and structured evaluation process that aligns with the ETH Competence Framework. Subcriteria within the rubrics allow us to assess additional competencies needed to fulfill the learning objectives. Communicating these rubrics to students raises awareness about the competencies they are developing, especially social and personal competencies, which are often overlooked.

Reflecting on the process of defining the report assessment rubrics requires significant time and resources. While the benefits of transparency are evident, other advantages may not be immediately obvious. Importantly, the rubrics serve as a valuable learning opportunity for students, making key competencies more visible. Additionally, the rubric text can be used as a reference for written feedback by the supervising team.

The report assessment rubrics have undergone multiple feedback rounds within the course team, educational developers, and competency experts. The most important feedback round will be when different supervising teams apply them to this year’s reports. Preliminary feedback from the supervising team indicated that while the rubrics enhanced clarity and transparency, their initial application was time-consuming. Some feedback noted that the rubrics were not suitably adapted for reports scoring below grade 4.75. In response, we will conduct a comprehensive feedback session and make necessary adjustments to the rubrics for the spring semester of 2025. Minor refinements will continue in the coming years, but the feedback suggests that the developed rubrics provide a solid foundation for report evaluation.

Given that written reports are the main product of various courses, we hope that the assessment rubrics we have created can also serve as a framework for assessing reports in other courses, as well as bachelor’s and master’s theses.

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Appendix

SUBJECT-SPECIFIC COMPETENCIES (to be specified by individual degree programmes) Knowledge of theories, concepts, and techniques and its application to specific fields	
Concepts and Theories Ability to understand and apply the basic concepts and definitions that are relevant for a scientific subject or a field	**Techniques and Technologies** Ability to understand and apply techniques and technologies in use within a specific scientific subject or field

METHOD-SPECIFIC COMPETENCIES Knowledge and application of methods to make sense of, and operate in, any context				
Analytical Competencies Ability to break down processes and systems into parts while understanding their interaction	**Decision-making** Ability to define a decision and a set of alternative actions from which to choose	**Media and Digital Technologies** Ability to access, evaluate, and use media and digital technology	**Problem-solving** Ability to define a problem and find solutions for it	**Project Management** Ability to manage projects and produce results

SOCIAL COMPETENCIES Competencies applied in the interaction with others						
Communication Ability to communicate with others in different contexts and forms	**Cooperation and Teamwork** Ability to build relationships with others to pursue common goals and achieve results in a constructive atmosphere	**Customer Orientation** Ability to approach relationships with others and society in terms of what you have to offer rather than what you need or want	**Leadership and Responsibility** Ability to motivate and inspire others and support others' achievements	**Self-presentation and Social Influence** Ability to present an authentic and professional image of self to others and motivate others to the adoption of a specific behaviour	**Sensitivity to Diversity** Ability to recognise differences among people and work with them	**Negotiation** Ability to advocate positions with an open mind and try to synthesise ideas from all viewpoints best

PERSONAL COMPETENCIES Competencies concerning self-management in the context of own work					
Adaptability and Flexibility Ability to adjust effectively to a changing environment and deal well with changes	**Creative Thinking** Ability to produce and implement novel and useful ideas	**Critical Thinking** Ability to analyse and evaluate situations and recommend courses of action	**Integrity and Work Ethics** Adherence to moral and ethical principles in the conduct of own work and in the relationship with others	**Self-awareness and Self-reflection** Ability to under-stand own strengths and weaknesses and enhance self-development	**Self-direction and Self-management** Ability to motivate oneself and organise own work in order to achieve results

Figure A1: The ETH Competence Framework (Copyright of ETH Zurich) with competencies assessed or fostered in the course presented marked in yellow ((ETH 2024), marked).

Criteria	Competencies assessed / fostered	6	5.5	5	4.5	4	<4
Task Interpretation & Problem Analysis							
Learning objective: Analyze, streamline and structure a real-world problem							
Key competence: Analytical competence							
Define the project with a focus on the interest of the Cantonal authorities	Problem solving, Customer Orientation	Identifies a creative, focused, and manageable topic that addresses potentially significant yet previously less-explored aspects of the topic, which are of interest to the cantonal authorities.		Identifies a focused and manageable/doable topic that appropriately addresses relevant aspects of the topic, which are of interest to the cantonal authorities.		Identifies a topic that, while manageable/doable, is too narrowly focused and leaves out relevant aspects of the topic.	Identifies a topic that is far too general and wide-ranging as to be manageable and doable.
Identify and formulate answerable goals and research questions	Analytical competence	All goals / research questions indicate a deep comprehension (e.g. system boundaries defined) of the problem and are concisly formulated		All goals / research questions indicate comprehension a of the problem. Formulation is non-ambiguous.	Goals / research questions indicate comprehension a of the problem but the formulation could be clearer.		Goal research questions do not show deep comprehension of the problem. Formulation is not concise enough
Scientific Competence & Argumentation (grade counts double)							
Learning objective: Adapt and apply known methods in a new context and deduct relevant suggestions for their "employer"							
Key competence: Problem solving							
Question and adapt known ideas or methods	Subject specific competencies, Creative Thinking, Critical thinking	All common, relevant approaches were considered, critically reviewed and adapted to serve the goals/question defined	relevant approaches were considered, critically reviewed and adapted to the goals/question defined	relevant approaches were considered, and adapted to the goals/question defined	relevant approaches were considered, and mostly fruitfully adapted to the goals/question defined	relevant approaches were considered, but not fruitfully adapted to the goals/question defined or most approaches are relevant but some are not	relevant approaches were NOT considered
Make necessary assumptions 1) where data is missing or not obtainable 2) for comparison 3) to define system boundary	Analytical competence	All assumptions make sense, are appropriatly chosen for the questions at hand and are clearly separated from scientific facts	All assumptions make sense and are clearly separated from scientific facts		Most assumptions make sense and are separated from scientific facts		Assumptions do not always make sense and/or are not clearly separated from scientific facts
Deduct suggestions/recommendations including advantages, disadvantages and limitations	Problem solving	The suggestions, which are most promising for the employer are concisely and prominatley described, inlcuding reference to possible limitations, advantages and disadvanteges	The suggestions are concisely and prominatley described, systematically inlcuding reference to possible limitations, advantages and disadvanteges	Suggestions are deduced from the results of the project and prominately described. Limitations, advantages and disavantages are generally mentioned.	Most of the suggestions relevant to the target audience, deduced from the results and are prominatley described.	Suggestions are made but are not always relevant or deducible from the results of the project.	The suggestions are hard to find and/or are not helpful
Describe limitations of project results	Critical Thinking	All limitations of the project results are discussed. It is made clear under which circumstances the results are valid and applicable. Possible solutions for the limitations are provided (e.g. outlook, experiments)	you could add for grade 6 that potential solutions to limitations are discussed, e.g. by providing an outlook, ideas for next experiments, interventions, etc.	All limitations of the project results are discussed.	Most important limitations of the project are discussed.	Limitations of the project results can be found in the report	Limitiations are missing or Some important limitations of the project results are missing.
Quality of report (grade counts threefold)							
Learning objective: Write a complete, concise and comprehensible report for employer following scientific requirements							
Key competence: Subject-specific competencies, Communication							
Quality of content (counts double)							
Structure of report	Subject-specific competencies, Communication	The structure of the report is always logical and makes finding specific information easy. The structure supports the story line and the key messages are clearly convey.	The structure of the report is logical and makes finding specific information easy. The structure support the story line. Key messages can be found.	The structure of the report is logical and makes finding specific information easy. The story line and key messages are not always easily found	The structure of the report is mostly logical and finding specific information is mostly possible.		The structure of the report is not very logical and information sometimes hard to find.
Quality of report parts *(see criteria below)*	Subject-specific competencies, Analytical competencies, Decision-making, Problem solving	All criteria for the different report parts exceed expectations: no flaws, no mixture of chapters, every sentence/paragraph in the right place (or at least 95-98% of the time :-))	All criteria for the different report parts are met	All criteria for the different report parts are met with very few minor flaws	Max. 2 sections contain flaws		Obvious flaws regarding the different report parts
Executive summary: respects it's form and conveys the most important findings and recommendations							
Introduction part: points out the relevance of the topic and builds up to the leading questions							
Methods: description is comprehensaible and relevant information is there							
Results: answer the questions introduced, description is concise, illustration supports key findings, no mixture with discussion part							
Discussion: covers relevant aspects, goes into depth, logically structured, comprehensible							
Conclusion/Suggestions: recommendations concise, logical and adapted to employer/settting							
The defined goals are the "red thread" throughout the report							
Formal quality (counts single)							
Formal quality of the report *(see criteria below)*		There are no flaws regarding formal criteria whatsoever	Formal criteria are met with very few exceptions	Formal criteria are met with only minor flaws	Formal criteria are mostly met with some obvious flaws in max. 1 criterium	Formal criteria are mostly met with some obvious flaws for several criteria	Formal quality has major flaws
The language used is appropriate, the terms are used correctly and precisely							
Correct citation, labels & indexes							
All maps, graphics and tables are correctly titled and numerated							
Appropriate and clean layouting							
The orthography is good. There are no careless mistakes (Flüchtigkeitsfehler)							
Project Managment: Working process, independence, organization, communication							
Learning objective: deliver defined project results within the given time frame and approporiate communication with employers and other relevant partners							
Key competence: Project management							
Work independantly and creatively (e.g. prepare and bring own ideas / suggestions to meetings)	Self-direction and Self-management, Creative Thinking	The group showed a lot of self-initiative, worked independently and creatively	The group worked independently and creatively	The group worked mostly independently and showed creativity	The group often worked independently and showed some creativity	The group only partly worked independently and/or showed little creativity	The group only partly worked independently and showed little creativity
Plan and organize your project	Project management	The group constantly took initiative on planning and organization of the project. The time scheduling was always done with foresight.	The group took initiative on planning and organization of the project. The time scheduling was done with foresight.		The group often took initiative on planning and organization of the project. The time scheduling was usually done with foresight.	The group took some initiative on planning and organization of the project. The time scheduling was rather improvised	The group did not take initiative on planning and organization of the project. The time scheduling was rather improvised
Communicate actively with coaches, experts, cantonal authortities and external experts	Communication	Communication was always deliberately chosen, concise and balanced (not unnecessary, not too little)	Communication was deliberately chosen, concise and balanced		Communication was mostly deliberately chosen, concise and balanced	Communication was sometimes deliberately chosen, concise and balanced	Communication was not deliberately chosen, concise and balanced

Figure A2: Report assessment rubrics.

Exploration labs: A high-quality PBL-format designed to equip students with career-critical competencies for industry

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Abstract

Project-based education is an established approach in engineering education to equip students with the necessary skills to address the highly complex and uncertain challenges they face in industry in a dynamic globalized industrial environment. The belief in the efficacy of project-based learning in conveying these skills has risen among educators, and a framework for designing effective, high-quality project-based learning formats has been proposed by Mergendoller (2018).

In this paper, a project-based learning format, the Exploration Lab, is introduced to address the research question: To what extent and through which elements does the EXL enhance career-critical competencies, and how do students compare it to traditional thesis projects? The format focuses on using real industry challenges to teach early-stage agile product development and innovation in an industry setting. The main elements of the format are described and linked to how they contribute to achieving high-quality project-based learning. Adding on this, a link to the ETH Competence Framework is made, elaborating on main competencies like problem-solving, critical thinking, collaboration, or communication the Exploration Lab aims to convey. Observations on key-learnings of the first cohort, including student self-assessments and industry outcomes, of this format are related to the competence framework, serving as initial validation of efficacy and highlight the Exploration Lab's alignment with high-quality project-based learning and competence-building goals.

In future works, more extensive approaches to measuring the effectiveness of this format could be explored. In particular, indicators of increased competence could be assessed using tools like pre- and post-project-participation surveys.

Introduction

Equipping students with the necessary tools and skills to overcome real-world challenges is increasingly recognized as a crucial aspect of modern education. The growing need for critical thinking, communication, and adaptability is essential for navigating highly complex and uncertain situations (Foster & Yaoyuneyong, 2016). Project-Based Learning (PBL) is a student-centered instructional approach that addresses these needs by emphasizing context-specific learning, active student involvement, and the achievement of goals through social interactions and the sharing of knowledge (Kokotsaki et al., 2016).

Shpeizer (2019) similarly observes that PBL offers a more engaging, learner-centered format that values autonomy, activity, and collaboration. Despite its potential benefits, the adoption and implementation of PBL in higher education have been gradual. One reason for this might be that linking project-based education not only to technical challenges, but to real industry innovations is extremely challenging, for example it requires a special environment with an industry partner who will allow students to actively work on their current challenges.

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However, despite slow adoption, the belief in PBL's efficacy is growing among educators worldwide, who see it as a means to help students master academic skills and content knowledge, develop future-oriented skills, and build personal agency for tackling life's and the world's challenges (Mergendoller, 2018). In this regard, an evaluation of Ngereja et al. (2020) showed that project-based assignments had a positive impact on student learning, motivation, and performance in both the short and long term.

Mergendoller (2018) highlight the increasing confusion about what constitutes high-quality PBL, proposing a framework that describes PBL in terms of student experience to provide educators with a shared basis for designing and implementing effective, high-quality PBL formats (HQPBL). The HQPBL-Framework states six required criteria, which are presented in the methods section.

While PBL itself is focused on how learning can be structured, one should not forget what should be learned; namely transferable skills and competencies. In this regard, La Cara et al. (2023) have recently published the ETH Competence Framework, contributing to the debate on why and how universities change to prepare future-ready graduates. This framework allows categorization of 20 transferable skills into the subject-specific, method-specific, social, and personal competencies.

Scope and research question

This paper examines the Exploration Lab (EXL), a program evaluated during its initial run from October 2023 to April 2024. Conducted through a collaboration between the ETH Feasibility Lab and Bühler AG in Uzwil, it involved eight ETH Zurich students from diverse fields. The study investigates the question: To what extent and through which elements does the EXL enhance career-critical competencies, and how do students compare it to traditional thesis projects?

The analysis is structured in three parts. First, we identify which components of EXL align with the six criteria of effective project-based learning, as outlined in the HQPBL framework. Second, using the ETH Competence Framework, we map how these components contribute to students' skill development. Third, a survey of all participants provides data on their self-reported skill levels before and after the program, as well as their views on EXL versus traditional thesis formats.

Background on organizing institution: ETH Feasibility Lab

The ETH Feasibility Lab was founded in 2019 by Prof. Mirko Meboldt and Dr. Stephan Fox from the Product Development Group Zurich, Department of Mechanical and Process Engineering, ETH Zürich, Switzerland. The lab aims to connect cutting-edge ETH technologies with market demands.

Many bold ideas are often dismissed as too risky for traditional industry commitments and too undefined to attract specific research interest. This 'Valley of Uncertainty' results in many ideas not being tested. The lab aims to reduce uncertainty with minimal resources, allowing innovative concepts to bridge this gap and qualify for further development. In this ecosystem, students act as 'know-how carriers,' learning to navigate early-stage innovation projects and launch their professional careers.

Initially, the lab conducted individual projects with one student working on a project for a single company. This phase resulted in foundational learnings that informed the development of the Lab's methodology for projects with high uncertainty.

Exploration Lab: A new PBL approach integrated with industry

From 2023 to 2024, the 'Exploration Lab' (EXL) format emerged, scaling project-based learning (PBL) to involve student teams exploring multiple ideas for a single company. New methods were developed to prioritize ideas based on initial testing outcomes.

Looking ahead, the Feasibility Lab seeks to expand the EXL's student pool and interdisciplinarity, inviting more companies to engage in exploratory projects or innovate in areas lacking defined expertise. Committed to inclusivity, the ETH Feasibility Lab refines its innovation methods and formats using continuous insights. The second cohort launched in October 2024, running until March 2025, with a 6-person lead team, 14 students, and 4 industry partners. The EXL framework is detailed in the sections below.

Mission and core principles

Building on the students' curiosity, we respectfully challenge the status quo and co-create innovations to inspire an agile exploration mindset among our partners.

At the core of the format is student curiosity, which acts as the primary filter through which all ideas and actions must pass. A strong focus is placed on validating ideas through experiments and rapid prototyping. The students are trusted to make informed decisions, based on the hypothesis that their curiosity is guided by relevant considerations, such as the viability, desirability and feasibility of the proposed projects. Additionally, students are empowered to debate all assumptions, with project leaders advocating for this right and aligning expectations with industry partners. This involves stepping outside our partners' standard procedures and processes to explore new possibilities and innovative solutions. Teamwork and stakeholder involvement are maximized to leverage diverse perspectives and our partners' expertise to enrich the innovation process. The team is united behind these principles, enabling it to resist being confined to traditional processes and thereby able to not only live but also inspire a culture of continuous exploration.

Team composition and structure

The team consisted of eight students with backgrounds in mechanical engineering and materials science. Among them, one was working on a bachelor's thesis, one on a master's internship, and six on their master's theses. The students were native speakers of German, Italian, and French, comprising one woman and seven men, aged between 20 and 30 years. The lead team comprised three individuals, each either holding a PhD in product development or having relevant professional experience in the field, all with startup experience.

The legal framework established an agreement for the program's execution without predefined technical projects. The idea generation and identification as well as the selection of suitable projects were integral parts of the project and students' mandate. Decision-making authority on what to work on rested with the student team and the lead team, not the company. This setup ensured that students only worked on projects that interested them, teaching them to allocate resources to promising projects and make decisions independently. To maximize stakeholder interaction, the agreement required the team to be on-site at least three days a week. This facilitated the flow of information and enabled spontaneous meetings with stakeholders.

Program overview

A broad timeline of pre-phase, main phases, and post-phase is shown in Table 1. The main phase of the program spans 26 weeks and is tailored to fit a masters' thesis. Students start into the program by familiarizing themselves with the methodology and partner companies, actively shaping the idea finding process. An exploration phase of 17 weeks allows rapid iteration on multiple topics, with the goal to find an individual deep-dive topic for in-depth work in the last phase.

	Timeframe	Activities	Involved Parties
Pre-Phase	July-September 3 months before start	Recruiting students, partner coordination, initial funnel Ideation	Lead team, partner companies
Ramp-Up	October **3 weeks**	Methodology introduction, familiarize with partners, ideate	Students, lead team partner stakeholders
Exploration Phase	October-February **17 weeks**	Rapid iteration (Powerthink, Hack, Sprint) on many topics	Students, lead team, partner stakeholders
Deep-Dive	February-March **4 weeks**	Individual, in-depth work on individually chosen topic	Students, lead team, partner stakeholders
Wrap-Up	March **2 weeks**	Report-writing, presentation	Students, lead team, partner stakeholders
Post-Phase	April 2-4 weeks	Grading of reports, administrative closing tasks	Lead team

Table 1: Project Phases of Exploration Lab - Total Project-Duration for Students: 26 Weeks (6 Months Full-Time).

Program-level methodology: Innovation cascade

The innovation cascade in the Exploration Lab is designed to make small initial investments when uncertainty is high and progressively larger investments as uncertainty decreases. Frequent Go/No-Go decisions are implemented to isolate the best ideas and stop working on less promising ones, allowing only the most viable projects to move forward.
The cascade consists of increasingly large micro-projects called 'Treatments' (see Figure 1):

- **Powerthink**: *Is it worth pursuing? What is the critical function?*
  A 90-minute workshop, involving stakeholders from the partner organization. This stage focuses on structuring the problem, identifying the core issue, and brainstorming potential solutions. (Total pre- & post-processing time: 4h)
- **Hackathon**: *What are potential solutions for the critical function?*
  A one-day event, where the team conducts research and rapid, low-fidelity implementation and testing of potential solutions. This provides a first approximation of their feasibility.
- **Sprint**: *Can we test the critical rapidly and validate the approach?*
  A 3.5-day project, to develop minimal but functional prototypes. This stage evaluates the feasibility of different approaches through practical implementation.
- **Deep Dive**: *Can we solve the minimal set of functions to test the business case?*
  A four-week focused project with individual work, where the documentation serves as a written document for the thesis. This stage involves thorough exploration and development of the chosen solution.

Projects should only advance sequentially through the stages: Powerthink to Hackathon, Hackathon to Sprint, and Sprint to Deep Dive. However, treatment stages can be repeated or revisited as needed. This focuses efforts on the most critical questions and deliberately leaving out less important aspects, thus avoiding overcomplication and reducing the risk of failing to achieve set goals.

The Exploration Lab's structured week design was iteratively refined to balance divergent and convergent activities, maximize uninterrupted development time, reinforce learnings, and ensure efficient planning and coordination. The final structure, shown in Tabl, optimizes both deep work and collaborative alignment.

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning	Build & assemble experiment	Analyze results	Idea generation	Retrospective, planning	Build, define focus
Afternoon	Experiment, get data	Stakeholder update, document results	Idea Generation	Prioritize, experiment design	Build, experiment
Treatment Type	Sprint	Sprint	2x Powerthink or 1x Hack	Retro / Buffer Sprint (½ Day)	Sprint

Table 2: Week Structure of Exploration Lab (Project Management).

Each week began on Thursday with a one-hour retrospective, where students reflected on key learnings, challenges, and potential improvements from the previous cycle. Following this, they self-organized into small project teams (2–3 members), selecting sprint treatments aligned with their interests and expertise. From Thursday to Tuesday noon, teams worked intensively on these treatments, ensuring uninterrupted problem-solving and rapid iteration. Tuesday afternoons were dedicated to presenting findings to industry stakeholders, facilitating external feedback and decision-making. Wednesdays were allocated for Powerthink and Hackathon treatments, enabling focused ideation and rapid feasibility testing before transitioning into the next iteration.

Topic-level methodology: The Five Finger Formula

The ambiguity and fuzziness of the early-stage innovation phase is extremely challenging. In this phase, it is especially important that all decisions in the process should be based on data and not only on assumptions and gut feelings.
To achieve this, the Five Finger Formula is the tool we teach to participants in the EXL to navigate high uncertainty and achieve initial results without a large budget. It fosters the optimization of 'learning efficiency' - minimizing resources spent on dead-end paths, thereby maximizing attempts to find viable solutions. Additionally, it serves a 'common language' to structure the early-stage innovation process and ensure consistent communication. The five principles of the formula are easily remembered by the first letters of each finger's name: T, I, M, R, L. An in-depth description of this method, including application examples, is provided by von Petersdorff-Campen (2024) with a quick overview in Figure 2. This tool is supplemented by various commonly known methods (e.g. Design-Thinking, Lean-Startup) on a case-by-case basis.

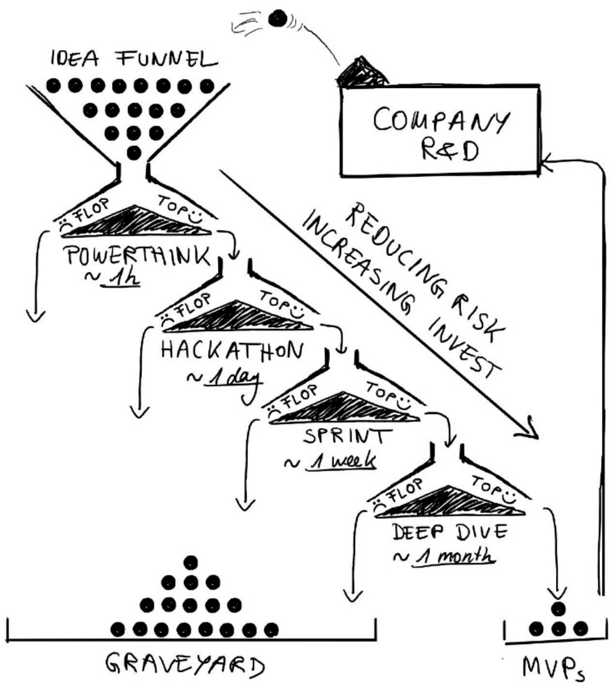

Figure 1: Idea Management System - Innovation Cascade. The innovation cascade serves as a guide to timebox project increments, with time and resource investments increasing as project risk is decreased. Decision gates at every stage serve to filter out less promising ideas and focus on the most promising ones.

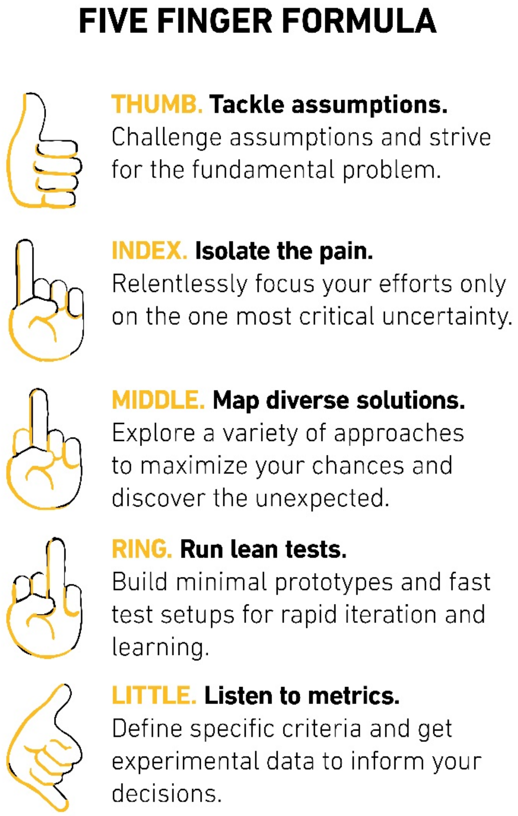

Figure 2: Uncertainty Management Method: Five-Finger Formula. The Five-Finger Formula acts as a mnemonic aid to help remember key focus areas at various project stages of projects with high uncertainty.

Methods

The impact of the Exploration Lab format on competence development is assessed in the following three ways:

Mapping of EXL program elements to HQPBL framework

According to the HQPBL framework by Mergendoller (2018), a PBL format must fulfill six factors to be considered 'high-quality' in terms of the students' learning experience and by extension competence development. The fulfillment of these factors is evaluated based on a structured list of EXL framework elements. The factors are:

- **Intellectual Challenge and Accomplishment**: Students learn deeply, think critically, and strive for excellence.
- **Authenticity**: Students work on projects that are meaningful and relevant to their culture, their lives, and their future.
- **Public Product**: Students' work is publicly displayed, discussed, and critiqued.
- **Collaboration**: Students collaborate with other students in person or online and/or receive guidance from adult mentors and experts.
- **Project Management**: Students use a project management process that enables them to proceed effectively from project initiation to completion.
- **Reflection**: Students reflect on their work and their learning throughout the project.

Mapping of EXL program elements to ETH Competence Framework

The ETH Competence Framework by La Cara et al. (2023) defines 20 competencies categorized into four domains: subject-specific, method-specific, social, and personal. To assess the relevance of competencies fostered in EXL, the lead team systematically reviewed all 20 competencies and identified up to four relevant links for each framework condition item.

Evaluating student learning outcomes and reflections

All eight participating students completed a survey to self-assess their competence levels pre-thesis and competence gains afterwards. Additionally, they were asked to compare the EXL to a traditional thesis (see Tabl for differences). Finally, each student also submitted a personal learning report reflecting on their key takeaways from EXL. These reports were analyzed in relation to the ETH Competence Framework, with notable observations highlighted.

Traditional Thesis	Thesis within Exploration Lab
Single topic	Multiple topics
Individual work	2/3 Team collaboration, 1/3 individual work
Academic setting (Majority)	Industry setting

Table 3: Key differences of thesis within EXL compared to a traditional thesis. Multiple topics are explored in a team-setting in industry.

Results

Mapping of EXL program elements to HQPBL framework

The EXL covers each of the HQPBL framework's factors in multiple ways, (see also Table 4 left column):

- **Intellectual Challenge and Accomplishment:** The topics are unsolved real industry challenges. Some have been unsolved for many years, making it challenging and leading to accomplishment when delivering results.
- **Authenticity:** The EXL is fully immersed in industry, thus the challenges we encounter are both authentic and immediately relevant. In this real-world context students see the direct impact and relevance of their work on a daily basis.
- **Public Product:** The work of students is critiqued and discussed with stakeholders, the lead, and other students on a weekly basis.
- **Collaboration:** The EXL requires students to work together extensively. For most of the project duration (four months), students collaborate on shared projects in teams of 2-3 people.
- **Project Management**: Students take responsibility for scheduling their update presentations as well as organize and plan their own tasks for the week, taking over project management duties.
- **Reflection**: Weekly and monthly retrospective sessions with the team ensure continuous reflection on the students' progress and learning.

Mapping of EXL framework elements to ETH Competence Framework

The competencies we believe are promoted most are shown in the right column of Table 4.

- **Subject-specific:** 2 competencies addressed through 10 elements
  These are required throughout the project but are explicitly mapped to only one EXL element – namely, the use of industry-standard tools to address challenges.
- **Method-specific:** 5 competencies addressed through 9 elements
  Multiple elements map to method-specific competencies. For example, frequent decision-making based on test-results, or the application of project-management methods are associated with the competencies analytical competencies, decision-making, and problem-solving.
- **Social**: 7 competencies addressed through 10 elements
  Many EXL elements relate to social competencies, particularly in the context of collaboration. Working in teams of 2-4 students and engaging frequently with stakeholders, supervisors, and customers provide opportunities to develop communication, cooperation and teamwork, and customer orientation.

- **Personal:** 6 competencies addressed through 14 elements
  Personal competencies in EXL are fostered through structured reflection, feedback, and autonomous decision-making. Key elements linked to these competencies include peer feedback sessions, individual coaching, stakeholder presentations, and self-directed project management.

Evaluating student learning outcomes and reflections

Student reflections

Due to confidentiality, project-specific details in the students' reflections are omitted. Student reflections were mapped to the same competence descriptors as EXL elements, summarized below in Table 5 and shown in Table 6.

	Present in # of Reports	Total Items	Competence Breakdown
Subject-specific	1	1	Techniques & technologies (1)
Method-specific	7	16	Decision making (6), analytical competencies (5), problem-solving (4), project-management (1)
Social	7	11	Communication (4), cooperation & teamwork (4), leadership & responsibility (2), customer orientation (1)
Personal	7	13	Critical thinking (3), adaptability & flexibility (3), self-direction & self-management (3), integrity & work ethics (3), creative thinking (1)

Table 5: Breakdown of Mapped Competence Descriptors in Students' Learning Reports.

Student survey

Figure 3 presents self-assessed competence ratings before and after the thesis. The left column displays pre-thesis ratings, from -3 (very weak) to +3 (very strong).
Problem-solving, together with cooperation & teamwork show a consistently strong rating (median +2, strong). Self-presentation & social influence shows the lowest median pre-thesis rating. Project-management also ranks weakly, with a median of 0 (average) but with a large spread (-2 to +3).

The right column shows the corresponding post-thesis competence changes, from -3 (significantly declined) to +3 (significantly improved). The largest median post-thesis improvements are observed in problem-solving (+2), project-management (+2), creative thinking (+2), and critical thinking (+2). No competencies show a negative change post-thesis. The smallest improvement is observed for sensitivity to diversity (+0.5) and integrity & work ethics (+1).

When asked to compare EXL to a traditional master's thesis, students unanimously ranked it as 'more engaging', 'more fun', and 'more motivating'. Additionally, seven out of eight students felt better prepared for industry. Finally, there was unanimous agreement that EXL offers more opportunities for personal growth. The complete results are shown in Figure 4.

HQPBL Framework	Elements of the Exploration Lab Format	ETH Competence Framework	
Intellectual Challenge and Accomplishment	Work on open, high-uncertainty topics.	Problem-solving	Critical thinking
	High autonomy in project management and stakeholder communication.	Communication Leadership & responsibility	Self-awareness & self-reflection Decision-making
	High commitment to create impact and quality results expected.	Integrity & work ethics	Self-direction & self-management
Authenticity	Work on commercially relevant topics proposed by industry partner.	Problem-solving	Customer orientation
	Students largely self-organize their choice of project and their activities.	Cooperation & teamwork Leadership & responsibility	Adaptability & flexibility Project-management
	Use of tool & process ecosystem of industry partner. (e.g. CAD, Python Programming)	Techniques & technologies	Concepts & theories
Public Product	Regular presentations to industry stakeholders incl. to C-level management.	Critical thinking Self-awareness & self-reflection	Media & digital technologies
	Daily presentations of progress to peers & supervisors.	Self-presentation & social influence	Integrity & work ethics
	Focus on frequent interaction with users/customers.	Communication Customer orientation	Sensitivity to diversity Negotiation

Subject specific | Method specific | Social | Personal

Table 4: Mapping of EXL Framework Elements (Middle Column) to the HQPBL Framework (Left Column) and Mapping to Competencies of the ETH Competence Framework (Right Column). Continued on the next page.

HQPBL Framework	Elements of the Exploration Lab format	ETH Competence Framework	
Collaboration	Teamwork of 2-4 people.	Communication	Adaptability & flexibility
	Regular shuffle of team composition.	Leadership & responsibility	Integrity & work ethics
	Close involvement of and co-working with industry partners. (e.g. Stakeholder)	Communication	Negotiation
Project Management	Autonomy in choice of topics and activities through multiple topic stages.	Project-management	Self-direction & self-management
	Frequent decision making based on test results is expected.	Decision-making Project-management	Creative thinking
	Application of project management and innovation methodology is expected.	Analytical competencies Critical thinking	Adaptability & flexibility
Reflection	Weekly team retrospectives on learnings, working mode and methodologies.	Self-direction & self-management	Self-presentation & social influence
	Bi-Weekly individual coaching sessions with student supervisors.	Project-management	Self-direction & self-management
	Regular moderated peer feedback sessions.	Leadership & responsibility Sensitivity to diversity	Self-awareness & self-reflection

Subject specific | Method specific | Social | Personal

	Quotes from students' written learning observations	ETH Competence Framework
1	Isolating the pain revealed that there was an underlying grand vision by one of the stakeholders. I finally truly understood where the uncertainties are and what is critical for success.	Analytical competencies; Problem-solving; Communication; Critical thinking
2	Being able to engage with our potential customers early in the development process has helped shape the path forward. I learned about the importance of not asking, 'What is the goal?' but rather, 'What is the problem?'	Decision-making; Communication; Critical thinking; Problem-solving; Customer orientation; Analytical competencies
3	Being precise and understanding the problem before diving into Critical Function definitions is essential. As the project moves forward (...) it becomes necessary to redefine the Critical Function to shift focus onto the areas of highest uncertainty. They're (Methodology Frameworks) never a one-size-fits-all solution. Engaging in discussions with the team and being open to be challenged on the Critical Function are crucial in finding a 'good' or the 'right' Critical Function.	Analytical competencies; Decision-making; Problem-solving; Adaptability & flexibility; Self-direction & self-management Decision-making; Project-management; Communication; Cooperation & teamwork
4	Projects are almost never developed in vacuum; very often it is people rather than technical issues that will determine the success of a project.	Techniques & technologies; Communication; Cooperation & teamwork
	The fact that there wasn't a predefined goal meant need-finding of what we even want to achieve was a fundamental part of our work every week. I learned how to find my way through a fog of uncertainty, how to figure out what our next step will be without even (fully) knowing where you're going yet.	Decision-making; Adaptability & flexibility; Problem-solving; Integrity & work ethics; Analytical competencies; Self-direction & self-management
6	In situations where uncertainties still exist, individuals often shy away from making decisions, preferring to pass 'the hot potato of responsibility' to others, avoiding holding it themselves.	Cooperation & teamwork; Integrity & work ethics; Leadership & responsibility; Decision-making
7	A key aspect of our collaboration is the ability to bring new perspectives to existing problems as an external team. Unbiased and without the operational blindness that can arise from long-term industry affiliation, we were able to develop fresh approaches and ideas.	Analytical competencies; Critical thinking; Cooperation & teamwork; Creative thinking
8	Making countless micro-decisions is important for high velocity innovation. Be persistent and don't get too attached to your ideas, be willing to pivot depending on what the data shows. If you want something, step up and take initiative.	Decision-making; Integrity & work ethics; Self-direction & self-management; Adaptability & flexibility; Leadership &

Subject specific | Method specific | Social | Personal

Table 6: Quotes from Students' Learning Observations Mapped to Relevant Competencies of the ETH Competence Framework.

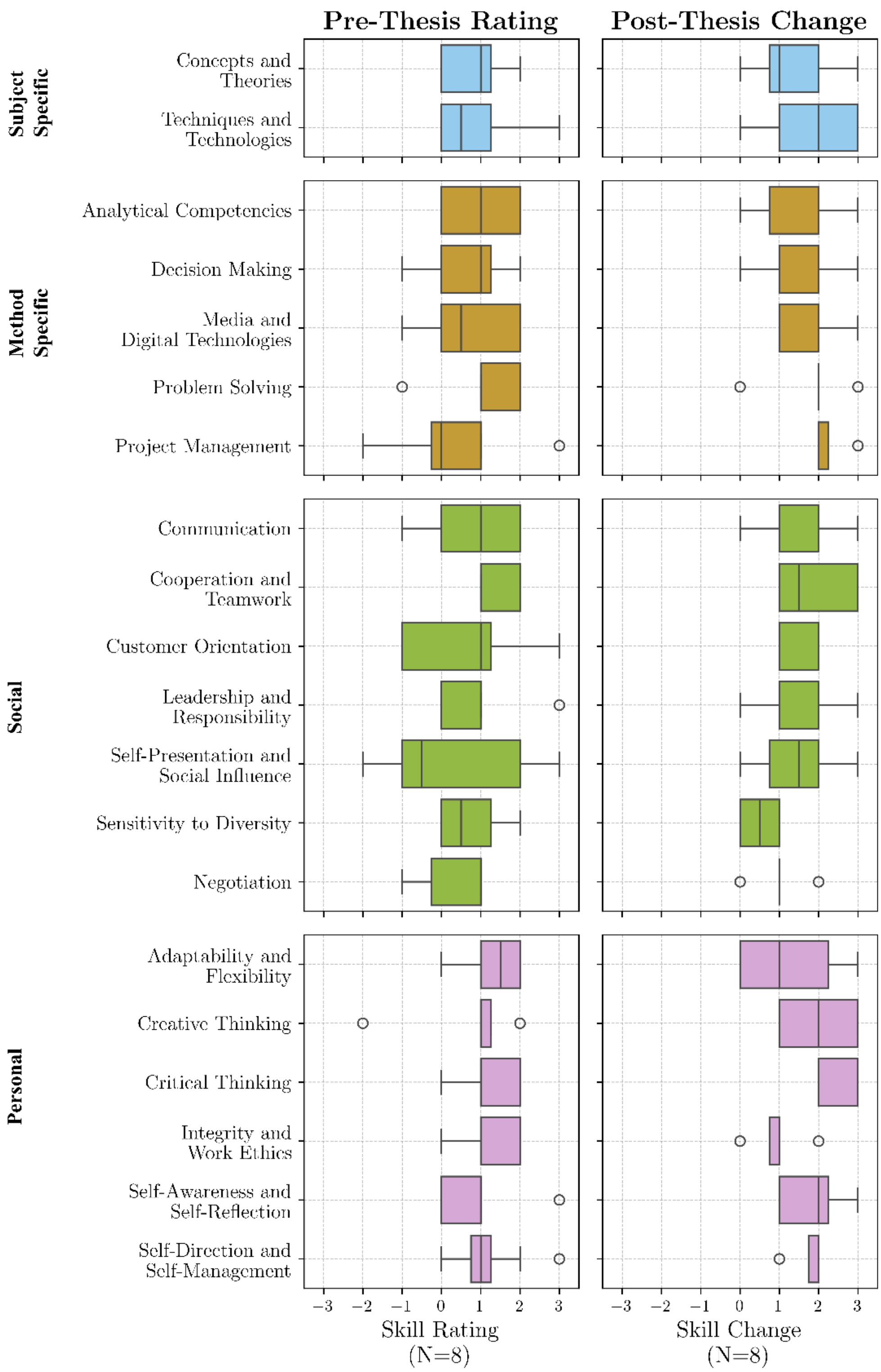

Figure 3: Student Responses to Survey on Competence Development During EXL. Left: Self-assessed pre-thesis competence rating, ranging from -3 (very weak) to +3 (very strong), sorted by competence category. Right: Self-assessed post-thesis competency change, ranging from -3 (decreased significantly) to +3 (increased significantly).

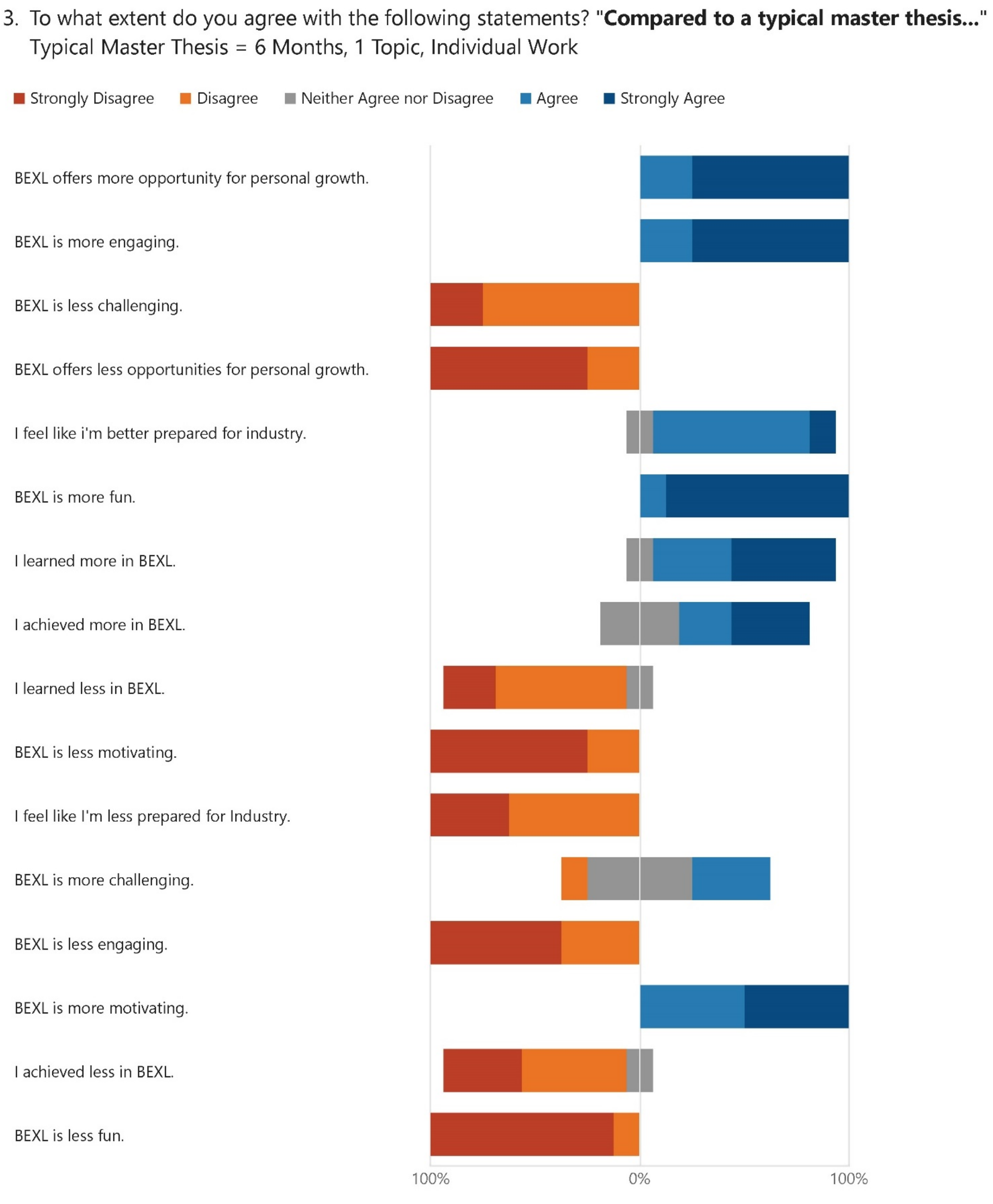

Figure 4: Student-Survey Results: Comparison of EXL to traditional (master) thesis. Note: BEXL is equivalent to our use of EXL, but reflects an old name, the B relating to Bühler AG.

Discussion

The EXL's real-world immersion and team-based approach appear to be highly effective in equipping students with essential skills like critical thinking, communication and adaptability. These skills, which Foster & Yaoyuneyong (2016) have shown to be critical for navigating highly complex and uncertain real-world challenges, may be career-critical in their later occupation. By mapping student outcomes to both the HQPBL criteria and the ETH Competence Framework, we observed that EXL fosters active engagement, practical experience, and industry-oriented skill development:

Mapping of EXL program elements to HQPBL framework

The EXL format addresses each of the HQPBL factors: Intellectual Challenge, Authenticity, Public Product, Collaboration, Project Management, and Reflection. Working on unsolved problems not only enhances intellectual rigor but also gives students a sense of accomplishment upon delivering tangible outcomes. The authenticity of the challenges faced allows students to see the immediate impact of their work. Frequent feedback accelerated competence development, and over time, students' independence increased, managing decisions and defending project strategies with minimal guidance. These findings align with broader PBL research, which shows real-world immersion encourages deeper, more transferable learning of e.g. problem-solving, communication, and adaptability. (Kokotsaki et al., 2016).

Furthermore, how often and in what way individual students sought feedback varied greatly. While some sought targeted input regarding both technical and personal skill development, others primarily requested topic-specific feedback. This difference underscores the importance of offering multiple feedback options - both formal and ad hoc - so that students can tailor their learning experience to meet their own developmental needs.

Overall, aligning EXL elements with HQPBL principles supports our hypothesis that EXL is a highly promising, high-quality PBL-experience fostering multiple dimensions of competence development.

Mapping of EXL program elements to ETH Competence Framework

Mapping of EXL's core elements against the ETH Competence Framework reveals broad coverage across subject-specific, method-specific, social, and personal domains. Subject-specific competencies are not tied to specific elements, except the required use of industry-standard tools by partners. As the EXL is intended as masters thesis, we accept this apparent lack of targeted development - subject-specific competencies are expected to be present from the students' preceding studies.

In contrast, method-specific competencies - fully supported by nine EXL elements -highlight the program's hands-on nature, and techniques like the Five-Finger Formula reinforce analytical, decision-making, and problem-solving skills.

Social competencies develop through team collaboration and regular stakeholder interactions, sharpening communication, customer orientation, and cooperative decision-making.
Personal competencies are fostered via reflection sessions, individual coaching, and self-directed project management, building autonomy and self-awareness. These gains were particularly salient during the latter stages of the thesis, when students began exercising higher levels of independent judgment and initiative.

Student learning outcomes and reflections

The individual learnings reports have students citing meaningful improvements in method-specific competencies (decision-making, analytical competencies, problem-solving), social competencies (communication, cooperation, leadership), as well as personal competencies (critical thinking, adaptability, self-direction). In parallel, the self-assessed survey shows the most pronounced competence gain for problem-solving, project management, and critical thinking. This shows that students' perspectives greatly overlap with our expectations of fostered competencies of EXL.

When comparing the students views of a traditional thesis compared to EXL, students unanimously found EXL more engaging, fun, and motivating, which we see as a strong indicator for efficacy of the format – a passionate, motivated team will perform much better and develop faster in comparison to a setting where team-spirit and motivation is lacking. Additionally, the fact that most participants felt better prepared for industry supports our intention of a purpose-built PBL-format to bridge the transition from academia to industry.

Observations on student development: Lead team perspective

The lead team (of which the authors are part of) is closely involved in the day-to-day supervision of the student, and thus was able to collect a diverse range of subjective observations on how different feedback mechanisms influenced the students and their development throughout the thesis. The most significant observations are shared as anecdotal evidence:

- The close supervision of students in early phases is crucial for the adoption of our methodology. Early on, short feedback loops are a key-enabler for effective competence development.
- As the project went on, students' independence significantly increased. In the second half of their thesis, students required noticeably fewer supervisor inputs and independently pushed decisions, took ownership and defended their approach.
- Students' behaviour in how they process feedback and ask for input varied drastically. Some students very proactively asked for specific feedback and guidance regarding competency and skill development. Others were more focused on topic-specific feedback rather than personal development.

Key-success factors & long-term sustainability of EXL

To ease the implementation of similar formats, we highlight once more the most important points. We believe these broad, overarching factors are paramount for creating an experience that is beneficial for all involved parties, and to enable long-term success:

- **Clear Legal Framework**: Establish a flexible legal framework early to address IP concerns and lower stakeholder engagement barriers. Ideally, all IP should transfer to the industry partner.
- **Open Problem Statements**: Partner companies should provide problem statements with open-ended solutions rather than rigid requirements. Students can be more innovative when allowed to explore freely.
- **Student Curiosity**: Allowing students to choose their topics ensures their motivation, which directly impacts project success.
- **Consistent Student Support**: While the methods are simple, consistent application is crucial. Senior support helps students stay on track with agile methods, especially when facing company resistance.
- **Ongoing Stakeholder Engagement**: Continuous communication with stakeholders ensures project handover and integration into the company, preventing the project from being sidelined.

In addition, we believe two final aspects must be fulfilled for long-term feasibility:

- First, supervision and coaching are critical for the success of initiatives like EXL. To scale the program, we need a pipeline of former students who are able to move into lead-team roles, leveraging their network and experience to mentor new participants, and shaping future iterations of EXL.
- Second, long-term partnerships and industry-demand for EXL is required. This is dependent on partners' being satisfied with the collaboration with ETH in the context of EXL and thus being open and willing to commit to future participation in EXL.

Conclusion & outlook

Summarizing, the results show that real-world immersion and team-based structures can cultivate a wide range of method-specific, social, and personal competencies, aligning with HQPBL principles. We see thorough coverage when mapping EXL framework elements to the ETH Competence Framework, from analytical thinking and problem-solving to communication and self-management. The student reflections and survey further confirm that EXL boosts motivation and industry readiness while explicitly enhancing project management and critical thinking skills, among multiple others. This synergy of authentic challenges, structured feedback, and team collaboration demonstrates a strong path for bridging academic objectives with professional practice.

We believe there is strong initial evidence for EXL presenting as an effective high-quality PBL-format, fostering a multitude of competencies through its many facets. The initial cohort has reported significant learnings, while the results of the second cohort are still pending. In conclusion, EXL appears to effectively enhance students' competencies, leading to motivated, adaptable graduates which are well-prepared for modern work environments.

Future work

We advocate for making project-based learning experiences on corporate innovation accessible to all students to better prepare them for their careers and to enhance the innovation capabilities of our workforce.

For a successful format to have a lasting and significant impact, there must be a setup that ensures continuity and scalability. Many factors need to be considered to achieve this, a selection of which we have outlined in the discussion: The learning outcomes for students are crucial. Industry partners must see tangible benefits, to continue providing students with access to real-world problems.

Continuous improvement should be the goal. In this regard, we acknowledge that the current conclusions are drawn on limited data of only eight participants' self-reported learnings, opinions, and our assessments. It is thus of even greater importance to conduct additional research on the efficacy of the Exploration Lab and similar formats. In future studies, a baseline measurement of other formats and traditional theses should be included, while expanding the pool of participants in EXL. This may lead to gaining a better understanding of success-factors of early-stage innovation and educating students on innovation methodology, and in turn pave the way for more PBL-Formats of high-quality and efficacy – for educating the innovators of tomorrow.

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Growing critical minds and cultivating solutions: Design Thinking as a useful toolkit and mindset for a project-based learning environment

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Abstract

In the face of contemporary global challenges such as food security, climate change, and socio-economic inequalities, fostering critical and creative thinking skills in higher education is paramount. Besides domain-specific expert knowledge, transferable competencies of graduates have become increasingly important in addressing current challenges by embracing complexity and integrating diverse backgrounds. This study explores the integration of Design Thinking within a project-based learning framework to enhance these competencies among agroecology students. The course 'Agroecologist Without Borders', offered at ETH Zurich, serves as a case study. Students engage with stakeholders and specialists, fostering a rich exchange of knowledge that directly impacts their learning outcomes. The course employs a transdisciplinary approach, integrating diverse disciplines and environments, with Design Thinking guiding students through understanding, empathizing, defining, ideating, prototyping, and testing solutions to real-world challenges. This approach serves as a model for future educational initiatives, highlighting the importance of fostering both critical and creative thinking in higher education.

1. Learning through projects as a nucleus for growing critical minds and creative solutions in the field of agroecology

In this study, we will explore the significance of project-based learning in higher education to create a transdisciplinary learning experience for students interested in the field of agroecology and sustainable agroecosystems at ETH Zurich. Using Design Thinking as an approach to project-based learning fosters not only methods and subject-specific competencies, but also social and personal skills. These include critical thinking, creativity, and problem management (Hajriani et al., 2025; Hawthorne et al., 2016), while also addressing contemporary crises such as food system resilience and nutrient cycling in a participatory manner.

Design Thinking originated at Stanford University in the 1960s as a highly human-centered and collaborative approach to problem-solving in real-world challenges. Since then, it has been applied across various contexts and fields. In education, it serves as an innovative approach for project-based teaching, fostering engagement with stakeholders and real-world issues (Brown, 2008; Jia et al., 2023; Ji Jiang & Pang, 2023).

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In our context, this teaching approach involves consistent and tangible engagement with stakeholders and students enrolled in the course 'Agroecologist Without Borders' during the spring semester at ETH Zurich. In this course, students engage in a participatory learning experience alongside stakeholders and specialists, fostering a rich environment where knowledge and insights are exchanged, directly influencing student learning through their design thinking projects. The course is created as a Design Thinking process and is based on a collaboration with the University of KwaZulu Natal in Pietermaritzburg, South Africa.

This article examines 'Agroecologist Without Borders' as a multifaceted project-based learning experience that integrates diverse disciplines and environments. We outline the course's conceptual framework, clarify its design principles, and discuss challenges encountered, aiming to advance educational initiatives in agroecology.

Agroecology - A journey towards transformation

Agroecology is a way of redesigning food systems, from the farm to the table, with the goal of achieving ecological, economic, and social sustainability (Gliessman, 2018). Moreover, agroecology is understood as a realm where science, practice, and social movements converge to seek a transition to sustainable food systems built upon the foundations of equity, participation, and justice (Méndez et al., 2013). In this regard, agroecology is deeply rooted in practice and real-life projects, where experiments and trials constantly feed scientific insights and vice versa (Nicholls and Altieri, 2018; Francis et al., 2020; Gliessman, 2022). Shifting toward agroecological and food system transformation implies building a global food system based on participation, localness, fairness, and justice (HLPE, 2014). Amidst climate emergency, biodiversity collapse, and ecological degradation, fundamental changes addressing systemic injustices, inequalities, and human-earth relationships are necessary, and students from a broad range of curricula are increasingly craving tools and approaches that would help address these pressing issues. For this reason, Agroecology is increasingly recognized as a crucial issue in education for tomorrow's scholars, professionals, and citizens (David & Bell, 2018).

Transdisciplinarity to bring realities closer to the learning environment

While system thinking and interdisciplinarity have been brought up in diverse agroecological curricula throughout recent decades (David & Bell, 2018), the possibility to exchange and ideate with a broader range of practitioners is bringing the students closer to the realities of the field (Pohl et al., 2020). Displaying subtly, and sometimes violently, the challenges and complexity that can be faced by communities across the world when questions and innovating towards agroecological transition. In this regard, transdisciplinarity appears as a complementary way to address agroecology and understand better how to engage in a transformative process. 'Transdisciplinarity is a reflexive research approach that addresses societal problems by means of interdisciplinary collaboration as well as the collaboration between researchers and extra-scientific actors; it aims to enable mutual learning processes between science and society; integration is the main cognitive challenge of the research process.' (Jahn et al., 2012 (3)) Through experiential learning that may embrace project-based learning as well as action learning, agroecology education can promote that transformation among both teachers and learners (Lieblein et al., 2004; Francis et al., 2020). A promising way to impel a change in students' learning and being is through transdisciplinary processes, including societal actors, various practitioners, thinkers, and researchers (academic and non-academic). Setting up transdisciplinary platforms in learning environments allows for exchanging, collaborating, practicing, and experimenting together toward a commonly defined goal and shared values. In order to ensure an enriching learning experience and achieve long-term objectives in such innovative learning environments, it is crucial to provide thoughtful guidance and planning regarding constructive alignment from the teacher (Lieblein et al., 2004; Biggs et al., 2022). If the learning environment is designed with this in mind, transdisciplinary projects can introduce creative perspectives on everyday actions and interactions for both teachers and students in a coherent way. Learning objectives are planned with the question in mind: what should students be able to do after completing the course? Learning activities and assessments are then designed to align with these objectives, ensuring that students have the opportunity to develop the targeted competencies and are assessed accordingly (Reynders et al., 2020; Biggs et al., 2022). In 'Agroecologist Without Borders,' we provide a space for reflecting on projects using transdisciplinary methods and offer opportunities to contribute by following the Design Thinking process. These active learning methods should also critique hegemonic approaches to producing and imposing certain findings and narratives, fostering critical thinking and creativity around these topics.

Finding oneself at the intersection of science and society

Environmental and agricultural students in institutions like ETH Zurich are expected to be change-makers, embodying the hope for a sustainable future. They are asked to develop meta-analyses of global socio-ecological dynamics and respond to the urgency of our current situation at various scales. However, given the vast scope of these challenges, it is essential to shape this educational process in a coherent and grounded way. This requires building bridges between disciplines, their real-life applications, and their socio-ecological impacts while also engaging with existing alternatives and enabling rooms for creative ones paving transformative paths.

To navigate what might seem like an overwhelming task, in a healthy and sustainable manner, students need room to digest, process and learn while actively experimenting, sharing and contributing to on-going societal questions, such as the one related to whom feeds us and how? Or in what ways are we handling our wastes and why?

For students, a semester can feel like an overwhelming accumulation of courses to complete alongside classes, labs, excursions, reports, and numerous exercises – often focused solely on passing and progressing through a demanding, high-pressure, and rigorous academic journey. This structure limits opportunities for students to pause, reflect, question, and process the knowledge they acquire.

In a vibrant political context where the universities are oppressing and silencing students asking themselves questions in relation to social and climate justice, it is also important to foster more liminal spaces for critical reflection. If scientists are asked to be rigorously present in the public debate in this context, establishing links between self-reflectivity and awareness is essential. Students should be encouraged to embrace diverse perspectives, be able to think outside the box, and adopt a fail-forward attitude. The teacher plays a key role as an enabler of space that can foster such approaches, initiating regular reflection loops to steer the learning experience in a meaningful direction (McLaughlin et al., 2022). Furthermore, while AI tools are increasingly useful for navigating studies, critical reflection is necessary to avoid becoming overwhelmed by algorithmic speculations.

While some universities deliberately allocate time and space for students to absorb lectures, engage in discussions, and self-document their learning, others prioritize competitiveness and performance at the expense of these reflective moments. Thus, universities occupy an ambivalent role, serving both as spaces for intellectual growth and potentially alienating environments. Recognizing this tension, educators can shape their courses as liberating platforms – creating breathing room and fostering porous exchanges that nurture critical thinking.

Finding oneself at the intersection of science and society, a myriad of tools exists to facilitate the journey back and forth and shed light on the potential for sustainable food systems transformation.

2. The conceptual framework of the course and the learning environment

The course

Historic context

'Agroecologist Without Borders' is a course offered in the Department of environment system and sciences D-USYS of ETH Zurich since 2015. During the pandemic, the shift to an online format facilitated participation and dialogue across continents in new ways, ones that have presented previously unimagined possibilities. In keeping with the participatory and transdisciplinary spirit of RUNRES project itself, we decided to exchange more closely with a wide range of key actors engaged in the transition towards a sustainable and equitable community. This multi-stakeholder group, led by the project manager and the postdoctoral researcher and composed of other researchers, agricultural extension officers, local university students, the school community, and staff, worked intensively with the ETH Zurich students.

The course welcomes master students of agricultural and environmental sciences, and since 2024, it has also been open to architectural students. The goal of 'Agroecologist Without Borders' is to introduce students to the complexity and challenges, both biophysical as well as socio-economic, inherent in agricultural development interventions, and to develop their science communication skills by producing outreach materials in the context of a given case study. In groups, students are invited to develop a science communication toolkit for The Bishopstowe Agroecology Living Lab (BALL) in Msunduzi, South Africa: Addressing agroecological transition in learning by doing. Over the last few years, the Sustainable Agroecosystems research group has organized this course around a case study related to an ongoing agricultural research project in Africa. For example, past courses studied efforts to support agroforestry in central Malawi or organic soil fertility management in Mozambique.

RUNRES project

Since 2021, the course has focused on the ongoing research and development project 'The Rural-Urban Nexus: Establishing a nutrient loop to improve city region food systems resilience (RUNRES). RUNRES is an eight-year project with the overarching goal of improving sustainable and resilient city region food systems in four sites across Sub-Saharan Africa: Arba Minch, Ethiopia; Kamonyi, Rwanda; Bukavu, DRC; Msunduzi, South Africa. Composed of a diverse and interdisciplinary team of academics and practitioners, the project objective is to support a circular food system predicated on the capture and processing of currently undervalued waste streams to provide locally sourced and sustainably processed nutrients capable of maintaining soil health and fertility. Although RUNRES is introducing numerous interventions such as municipal scale composting, enhanced small-scale food processing, or fecal sludge pyrolysis to facilitate this change, 'Agroecologist Without Borders' has focused specifically on three innovations co-developed within the team led by Prof. Odindo at the University of KwaZulu Natal in Pietermaritzburg, South-Africa: 1) The 'Decentralized Wastewater Treatment Systems' (DEWATS): a way to improve the sanitation in a rural South African school, while also contributing to community-based economic development and environmental health. 2) The DUZI-Turf co-composting facility: producing compost from sewage sludge and urban green waste. 3) The Bishopstowe Agroecological Living Lab: a knowledge center, learning, and experimental platform based in the outskirts of Pietermaritzburg and aimed at scaling out circular bioeconomy and agroecological innovations.

Thus, the objective of the course was to provide the students an opportunity, in a structured and facilitated environment, to co-develop locally appropriate communication and outreach material capable of supporting the successful adoption of this novel technology among local communities.

Learning goals and ETH Competence Framework

There are seven distinct learning goals set for the students in this class:

1. Students analyse a concrete example of an agricultural research project.
2. Students broaden their understanding of environmental and socio-economic challenges within a Living Lab.
3. Students engage with positive and empowering frameworks that encourage critical reflection and action on the transformative responses needed within agricultural and food systems.
4. Students articulate the complexities and challenges involved in agricultural development interventions.
5. Students develop science communication skills by producing materials in the context of the given case study.
6. Students practice their project management skills.
7. Students engage in a Design Thinking process.

For each goal, a set of competencies borrowed from the ETH Zurich Competence Framework has been established. In this regard, we aimed to foster not only subject- and method-specific competencies but also to actively work on more personal and social competencies of the students.

Structure, tools, and learning environment

The class is structured with various sessions, ranging from theoretical inputs to guest lectures that provided inspiration through diverse case studies to key presentation moments where each group updated their peers in front of the class and a time for discussing it in plenum with lecturers and students.

The course provides 4 hours of direct instruction per week during the spring semester and is worth 3 ECTS credits. Following student feedback, one additional credit was incorporated. The assessment consists of a graded semester performance, which includes a group project focused on developing a scientific communication toolkit for a selected project, alongside an individual assessment composed of a two-page personal reflection on the project.

The teaching strategy emphasized encouraging collaborative work on students' projects, fostering a positive atmosphere by sharing food during the break, starting with a reading session as a way to land in the space, and bringing important questions on critical thinking for teaching and check-out board to express where one finds themselves at the end of the course and aims to host and provide safe space for discussion, conflicts, and understanding.

The course is supported by an innovative transdisciplinary framework and online tools such as Zoom, WhatsApp, and Miro. These tools were used to map the system, gather data, produce insights, and reflect on the system's main components. Zoom is utilized for general course sessions, involving active participation from lecturers, project managers, and other guests located in South Africa. WhatsApp facilitates direct communication, especially with the South African team, as it is the most convenient way to initiate meetings or catch up. Miro is an effective tool for observing student progress during exercises and guiding them step-by-step through the various topics and perspectives covered in the lecture.

Ultimately, the course took place in the SAE Greenhouse Lab at ETH Zurich, an old greenhouse now used as a teaching and outreach space. The greenhouse, filled with diverse plants – tropical ones and those from other students’ projects – offers a uniquely inspiring environment. This unique tool is a major element that provides a cocoon-like feeling for the students, allowing them to grow alongside the spring plants around them.

Creating an appropriate environment with Design Thinking as an underlying process for project-based learning

Different layers in the course

We identify three different layers in the course (see Fig. 1). Project-based learning is a guiding educational approach, and Design Thinking is one process to follow while working on real-world challenges in a structured way. Through this applied project-based learning approach in the course, students are encouraged to take ownership. The design thinking process enables them to engage in regular check-ins. The process is also structured in a way that allows students to draw from multiple disciplines, helping them connect different subjects from their curriculum, such as nutrient cycling and environmental project management. Throughout the process, students' input is used to refine the project experience for future classes and nourishes iterative adjustments. Furthermore, we believe this course provides them with valuable insights and tools applicable to other courses and their future professional endeavours. Students need to communicate complex systems, topics and matters comprehensively to a diverse array of stakeholders, from farmers to school kids. The students remain integral to this project, as it is in collaboration with them during the 'Agroecologist Without Borders' course that we co-develop tools and resources to fortify their skills.

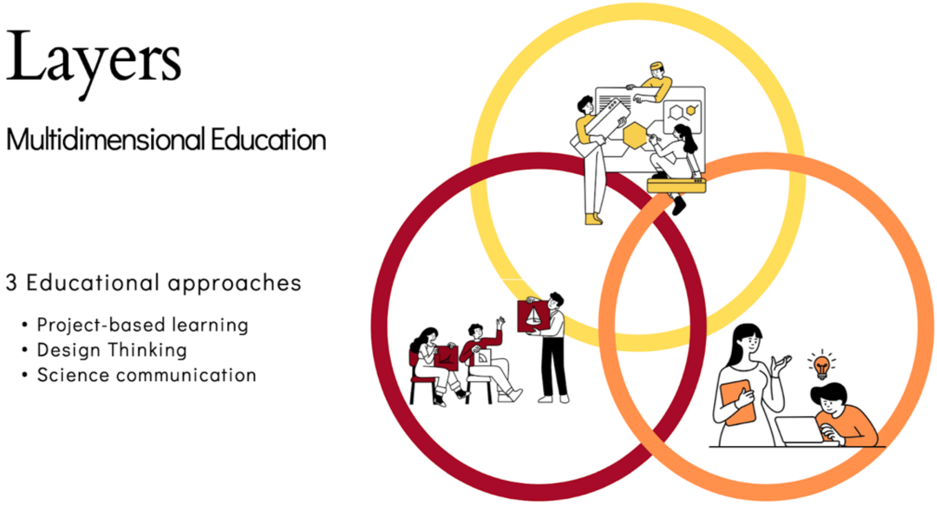

Figure 1: Three layers in the course.

For the Design Thinking process, we follow the 6-step-model from the d-school at Hasso-Plattner Institute with the following parts: Understand, Empathize, Define, Ideate, Prototype, and Test, see Fig. 2 (Meinel & Leifer, 2020). The first two steps, 'Understand' and 'Empathize,' are crucial to understanding the challenge or the problem deeply. The students also reflect about their own point of view and their disciplinary background to be aware about the lenses they are looking at a challenge. So, students should collect diverse data and insights in this step to get a broad overview and a deep understanding of the topic at hand (Brown, 2008; Tschimmel, 2012).

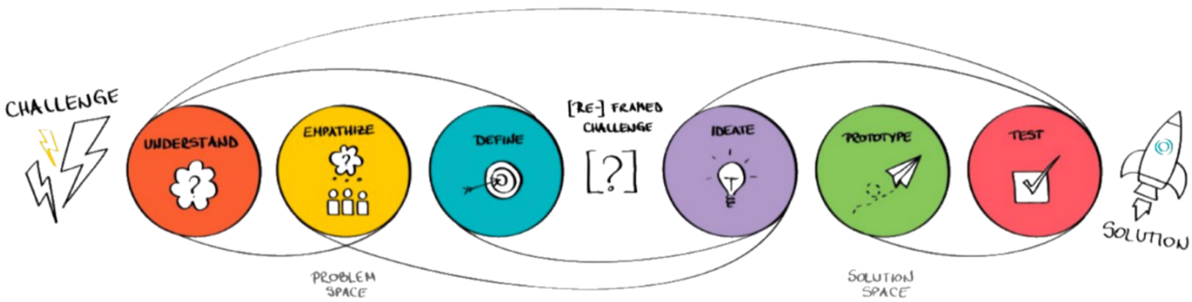

Figure 2: Design Thinking process. Adapted from HPI (Brown, 2008; Meines & Leifer, 2020).

To bridge the gap between the ‘Understand’ and ‘Empathize’ phases and the subsequent stages of Design Thinking and to equip students with tools for managing diverse information, we provide them with the skills to create clear and concise communication materials. The process begins with expert input and lectures on challenges in the South African living lab, followed by extensive information gathering on science communication in small student groups. This approach transforms the complex insights gained during the 'Empathize' phase – from interviews with South African stakeholders, online research, and expert exchanges – into a clear and digestible problem statement for all participants. The students need to critically evaluate the quality of their research information pieces and make sense of them to extract a well-defined problem statement from a diverse number of single insights as a next step. A challenge here is also to unpack the insights every student got and collaboratively work on a clear problem statement, which will serve as a guiding sentence for the solution space (ideate, prototype, and test phases). This process ensures everyone has a shared understanding of the challenge before moving towards solution-oriented phases (Beligatamulla et al., 2019). In the 'Empathize' phase and the subsequent 'Define' phase, we focus on the problem itself. The goal is to deeply understand both who we are as a collaborative team, to recognize our own perspectives, and to gain a comprehensive understanding of the stakeholders involved. Who are the main actors involved? What are the main needs to focus on? In what environment is this project unfolding? What influences the lived experience in this given context? In these first two steps, the problem or challenge at hand is central. In teaching, we must guide our students to broaden their perspectives, encouraging them to reflect on their own experiences and viewpoints while considering the lenses through which stakeholders view the given challenges. In the 'Ideate' phase, students transition into the solution space, generating multiple ideas based on their insights during the first phases in a short time. Following this, a prototype is selected, worked out, and tested. Design Thinking is of an iterative nature. If the students feel the need to better understand the context during the process for example, they might need to go back to the empathise phase and conduct further investigation. The mindset of growing personally by undergoing the Design Thinking process back and forth and learning from failure in early prototypes, and tests is one of the founding principles of this approach.

Science communication as a further competence layer in the course

In addition to the Design Thinking process in the project-based learning environment, the course emphasizes developing science communication toolkits tailored to diverse target audiences. Communicating complex scientific concepts to diverse audiences, including non-experts, remains a significant challenge in academia. By focusing on science communication, the course aims to bridge this gap. Offering science communication training to agriculture and environmental students, provided by the edumedia team of ETH, is essential for reaching a wide range of audiences and fostering food system transformation. These courses enable students to translate complex scientific concepts into accessible and engaging information, making it easier for stakeholders – such as policymakers, farmers, and the public – to understand and act. By enhancing their communication skills, students can develop tools for a better understanding and application of sustainable practices, support innovative solutions, and drive meaningful change in food systems, ultimately contributing to a project aiming for a more resilient and sustainable future.

In class, we reflect on the quality of their insights and mirror them back to the collaborators in South Africa to make sense of the insights in the light of the culture of our partners in the global south. Similarly, during the testing phase, it's important to creatively position the prototype within a communication framework that effectively engages feedback providers. Science communication can be integrated into the Design Thinking teaching approach in a deliberate way and enriches the transferable competencies fostered in this course further.

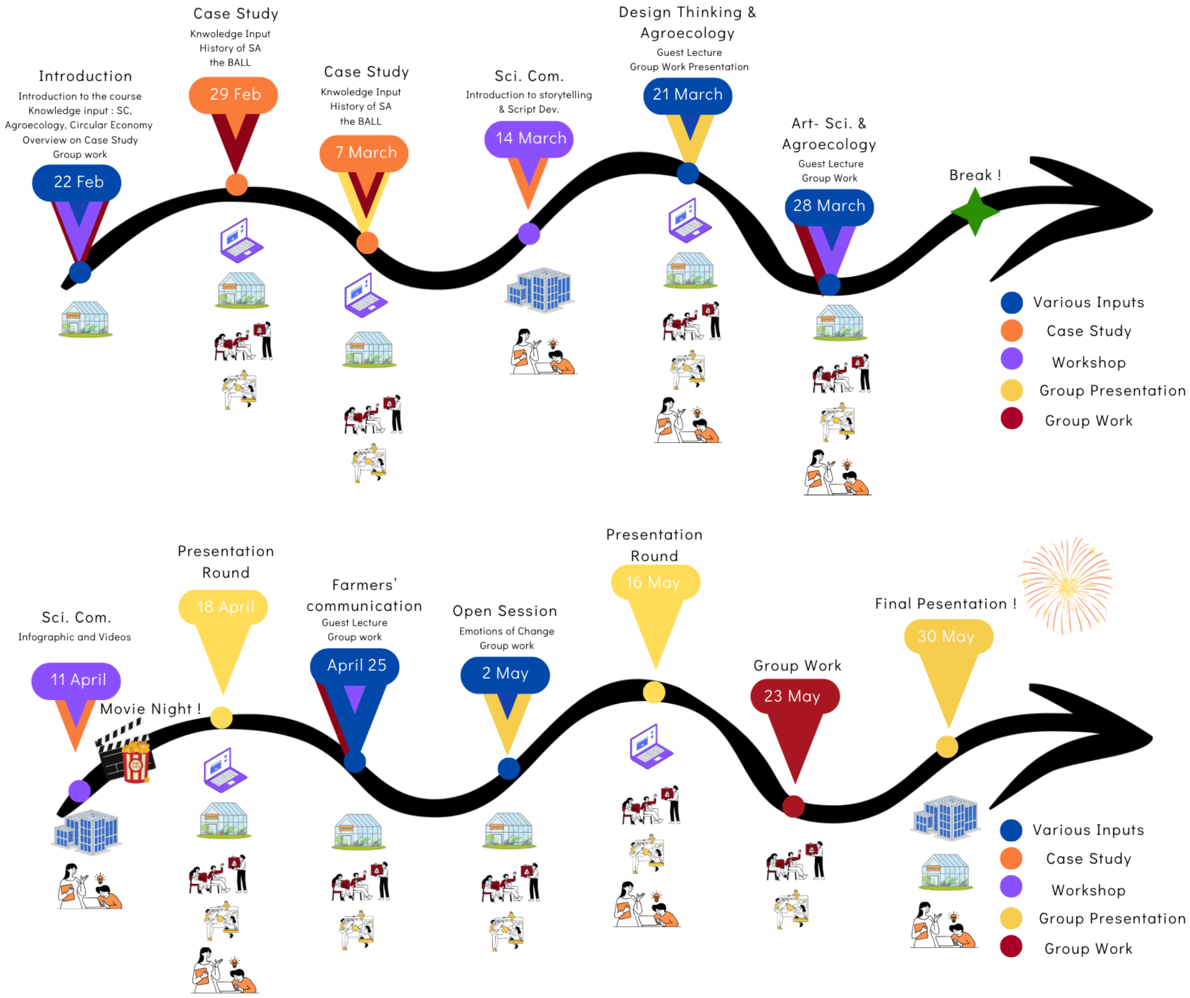

Figure 3: Overview of the course structure.

3. Fostering and assessing transferable competencies with a focus on critical thinking and creativity

Creativity through criticality

Two of the primary competencies fostered during this course were critical and creative thinking. Design Thinking as a teaching method supports critical minds in various ways. In the first step, *Empathize*, students need to critically evaluate how to approach their challenges. Who can be a valid interview partner to understand the needs of the stakeholders better? Compared to all insights in the *Empathize* phase, what does the information tell us about our own assumptions and the reality we have approaches a bit closer? Students need to come up with creative solutions about how to dig deeper into the topics at hand. About whom to approach for an interview or survey and in coming up with innovative ideas about solutions based on the identified needs of the stakeholders. Sometimes it can be hard to leave your own assumptions and solutions in mind behind you and train to be open to perspectives of people involved in a certain challenge.

To be competent in critical thinking is an important indicator of both academic and professional success (Castaño et al., 2023). To foster critical thinking and creativity in higher education, it is essential to set learning goals and plan activities and assessments that centers them both (Reynders et al., 2020) instead of leaving them develop accidentally. The ETH competence framework displays the wide variety of transformative competencies that should be fostered throughout a study program. To reach the goals in this competence area, study programs need to involve the lecturers to systematically integrate transferable competencies in the curricula. Focussing on Critical Thinking, the ETH competence framework[2] defines this as a personal competency and as 'the ability to analyse and evaluate situations and recommend courses of action.' However, a crucial aspect often overlooked in this definition is questioning normalized narratives. Critical thinking involves multiple layers of integration, discernment, and the ability to think beyond surface-level understanding, and this ability needs to be trained. In the course 'Agroecologist Without Borders', we build upon Bell Hooks' perspective: 'Critical thinking involves first discovering the who, what, when, where, and how of things – finding the answers to those eternal questions of the inquisitive child – and then utilizing that knowledge in a manner that enables you to determine what matters most.' (Hooks, 2010, p 9). Design Thinking as the underlying teaching method, builds upon the mindset of understanding the needs and perspectives of the stakeholders and then prototype and test artifacts that are of high relevance to the challenge in focus. The Design Thinking process enables a growth mindset and a culture of learning from mistakes and, digging even deeper into topics, and understanding perspectives of others even better to get prototypes that are relevant, innovative and a good fit to the challenges at hand. Creativity and critical thinking are, therefore, to be constantly encultured in a Design Thinking learning environment, and students have a great opportunity to train these competencies with their peers and with the lecturer in the position of a guide at the side.

Given the fast pace of the semester, the layered structure of the course, and the substantial workload assigned to students, this course aimed to create space for these curious questions to emerge and unfold. In this regard, the classroom setting and associated processes are crucial. Research suggests developing critical thinking requires integrating theoretical knowledge with professional practice (Bezanilla et al., 2019). This is where project-based learning becomes crucial, preparing students for professional life by making them service providers for the projects presented. In real-world projects, students can apply their theoretical knowledge and integrate perspectives from their learning environment in class and the project stakeholders while also practicing the ability to anticipate the consequences of their actions and positions within the project.

Creative Thinking is described in the ETH competence framework as 'the ability to produce and implement novel and useful ideas.' For our course, creative thinking is closely linked with imagination, which is central to the ideation process of design thinking. Here, imagination serves to transcend the confined limits of dominant narratives. As Bell Hooks states: 'Imagination is one of the most powerful modes of resistance that oppressed and exploited folks can and do use.' (Hooks, 2010, p 62). Imagination serves a crucial role in fostering critical thinking, enabling individuals to transcend existing paradigms and co-create new ways of understanding, comprehending, and being. While it can push students beyond their comfort zones and sometimes be overwhelming, this process is essential for developing the discernment needed to navigate knowledge and context effectively. Imagination supports critical thinking by challenging normalized narratives and encouraging deeper inquiry. This journey involves constructing well-founded arguments and developing the ability to critically assess various perspectives. Consequently, students are better equipped to adapt and respond to complex situations in an informed manner. In this process, the teacher plays a significant role (Sasson et al., 2018). If students experience a lecturer to take a stance, explicate the own viewpoint and feed well thought arguments into discussion and hear other perspectives, students are likely to feel encouraged to also develop and advocate for their own standpoint as well as develop and discuss their arguments with their peers.

Fostering creative and critical thinking: Insights from student feedback

To foster creative and critical thinking deliberately in class, it is essential to provide diverse tools and environments that encourage questioning, reflection, and creation. In this course, several elements were implemented to achieve this goal. Each session began with a 15-minute reading from a chapter of Bell Hooks' book, with topics selected based on recent discussions

[2] ETH Competence Framework retrieved from www.ethz.ch/comp-teachingstaff

or upcoming lecture themes. Additionally, resources such as books, links, and insights were shared in the course reader, on Moodle, or in a small library gathering books and diverse literature, all as tools to enrich the learning experience.

The effectiveness of these methods is reflected in the students' feedback. The unique classroom setting was highly appreciated, as one student noted, 'Holding class in the Greenhouse offered a refreshing energy for learning and made group/class work engaging.' Another student echoed this sentiment, stating, 'The greenhouse is a very amazing learning space!' The interactive nature of the course was also highlighted: 'I liked the instructiveness of it, and we saw your engagement. We felt like you were invested in the course and were thinking about how to improve it and how to make us feel better.' Students valued the safe environment for exchange and critical reflection: 'The lecture in the Greenhouse and the number of students provided a safe environment for exchange and critical reflection. In my opinion, the conditions couldn't have been better. I really enjoyed this type of lecture and found it very enriching.' These testimonials underscore the importance of creating a supportive and dynamic learning environment that facilitates both creative and critical thinking.

Assessing process vs. outcome

In Design Thinking, the iterative aspect of prototyping serves as a medium for constant adjustment, ensuring that the outcomes are tailored to the target audience. This iterative process involves multiple steps to refine the prototype, which can sometimes be overlooked, potentially leaving students frustrated if they perceive the lecturer as only outcome-focused. However, the process itself is fundamental, and these exchange sessions are crucial for emphasizing its importance. The process serves as the glue that unifies the various components of the course and acts as a driving force for continually improving quality. Alternative assessment methods, such as rubrics, have the potential to support students not only in planning their projects but also in reflecting on them (Reynders et al., 2020). By engaging in these iterative and reflective practices, students develop a deeper understanding of both the content and the methodologies, fostering a more comprehensive and critical approach to learning.

As Bell Hooks emphasizes, 'critical thinking is an interactive process, one that demands participation on the part of teacher and students alike.' (Hooks, 2010, p 9). In this regard, a strong emphasis is placed on process-oriented approaches, both for learning activities as well as for the assessment methods in the course. This becomes evident in the regular in-class exchanges where students share their progress, insights, and needs with the learning team. The frequency of these encounters underscores the transformative nature of processes rather than focusing solely on the final outcomes presented at the end of the course. Moreover, we developed a rubric to assess critical thinking and creativity objectively and learning-oriented (Reynders et al., 2020). Rubrics are evaluation grids that explicate and ease the assessment process, for example, for oral presentations, lab works, grading a thesis. As the criteria are clearly communicated to the students through the rubric grid, assessment gets more objective. The lecturer needs to thoughtfully develop an evaluation grid to use for a lot of students and, therefore, get better-informed grades. Once the grid had been developed, it could be reused, adding transparency to the grading practice. The following grid in Figure 4 shows a practical example from the described course. It was used in the oral exams and served as criteria while the students were presenting their prototypes to the audience.

Organization (1pts)	The presentation was clear and well organized
	The group presented the target audience, the topics and the problem they want to tackle
	The group provides clear and comprehensive explanations; reasoning is well-structured and detailed
	The prototype/project was answering the problem chosen by the group
Content/criticality (2pts)	The group understood well the content of the project and is able to display it through their work – Available information / Key elements
	The group interpreted the information insightfully / accurately
	The project outcome meets/answers the problem tackled by the group
Creativity (2pts)	Originality – The Project demonstrates highly original thinking and unique and novel ideas
	Elaboration – the ideas are fully developed with great detail and complexity
	Flexibility – The group show exceptional ability to shift perspectives and approaches
	Risk taking – The group has taken significant creative risks and explores unconventional ideas
	Expression – The group expresses ideas with clarity and impact
Context (1 pts)	The prototype is adapted to the target audience
	The group consistently reflects on own biases and assumptions; adjusts thinking accordingly
	The prototype is adapted to the south African context – more specifically the BALL

Figure. 4: Rubric grid for assessing the students based on the learning goals.

Ultimately, the course enables us to turn students' work into tangible communication tools for the project. Over the past year, the games, posters, zones, and digital platforms have been used on-site and shared with various stakeholders. For instance, the urine-diversion toilets at the Knowledge Centre and the school where the DEWATS center is installed feature infographics and materials that explain the processes of waste valorization aimed at schoolchildren and the broader audience visiting the space.

4. Discussion

Questioning hegemonic narratives

The course's unique setting, which integrates a project based in South Africa and fosters creativity and critical thinking, has sparked significant and challenging debates. One of the primary challenges was that students were initially unfamiliar with the context in which they had to produce their prototypes, mostly science communication materials. This unfamiliarity exposed them to different realities, prompting a process of learning and unlearning various worldviews and contexts.

Transnational collaboration, as implemented in this course, serves to train students in a globalized world. By engaging in such collaborations, students can limit CO2 emissions associated with travel while initiating discussions grounded in concrete projects and needs. This approach has practical challenges, as it sets a degree of discomfort for students in navigating a context they don't know well and requires them to be curious enough to understand the specifics of the context and gain enough understanding of the situation in a short amount of time. However, it also encourages a critical examination of worldviews. The continuous exchange with practitioners, lecturers, and academics centers on non-European voices around questions related to agriculture, food systems, agroecology, and circular bioeconomy in a way that connects the students to other realities. For example, the students were invited to critically examine the colonial legacy of agronomy in the South African system, such as apartheid's impact on food sovereignty and land access. Complementarily, all these inputs highlight the necessity of decentering European/hegemonic narratives in an academic context and offer possibilities to decolonize knowledge and academic practices. It is beneficial for the learning process to make these underlying processes and interconnections explicit and reflect on them deliberately on a regular basis.

Bringing decolonial methodologies

The course facilitated discussions on the hegemonic narratives perpetuated by science and the imperative to decolonize academia, curricula, and ecological practices. Agroecology emerged as a strong proponent of decolonial approaches, emphasizing the importance of indigenous voices being heard and acknowledged. The co-creation of knowledge is fundamental to supporting food system transformation and agroecological transition. This involves developing learning exchanges where farmers, scientists, and students collaboratively analyze and co-develop solutions to implement these agroecological practices. Integrating agroecological principles into curricula emphasizes ecological and social sustainability over exploitative and extractive-focused models, teaching students to work with rather than impose upon local ecologies and knowledge holders.

A decolonial approach to teaching requires not only acknowledging dominant epistemologies that can still be present and infused in our way of relating to one another and the knowledge we bring but also actively creating space for alternative ways of knowing. Engaging with transdisciplinary and community-based methodologies allows students to critically assess their own positionality, biases, and assumptions. Structured reflexivity exercises help students examine their backgrounds, biases, and roles in knowledge production while exploring power dynamics in agricultural extension, development projects, and global agrifood governance.

Decentering Western paradigms fosters deeper engagement with agroecological practices, which often derive from lived experiences rather than only technical expertise. This shift encourages students to think beyond extractive knowledge production and toward reciprocal, situated learning. By integrating decolonial methods into pedagogy, the course not only enriches scientific discourse but also contributes to more just and contextually relevant solutions for food system transformation. This includes shifting away from traditional classroom settings to explore new ways of engaging with the space, the project, the questions raised, its limits, and the ways in which the project is still continuously developing. Encouraging collaborative, non-hierarchical learning structures where students, educators, and practitioners contribute knowledge is essential for this transformation.

Integration of Design Thinking for project based-learning

The integration of Design Thinking into the 'Agroecologist Without Borders' course at ETH Zurich has proven highly effective in cultivating both critical and creative thinking skills among students. This approach aligns with the core objectives of agroecology, which seeks to redesign food systems for ecological, economic, and social sustainability. Engaging students in real-world, transdisciplinary projects has created a rich learning environment that bridges theory with practical application. Rubrics as an assessment tool have further enhanced this process, providing students with structured reflection opportunities and offering lecturers a more objective method for evaluating both process and outcome.

One of the key strengths of this course is its emphasis on stakeholder engagement, participatory learning, and intercultural collaboration and exchange. This not only enhances the relevance of the projects but also helps students develop essential skills in science communication and project management. The use of design thinking methodologies, particularly the six-step model from the d-school at Hasso-Plattner-Institute, has been instrumental in guiding students through the process of empathizing with stakeholders, defining problems, ideating solutions, prototyping, and testing. Design Thinking could be beneficial for other teaching contexts as well if there are clear real-world challenges to work on. Design Thinking as a teaching method is beneficial if lecturers aim to integrate domain-specific competencies with transferable competencies like collaboration, creativity, and critical thinking. If the lecturer explicates their own viewpoints and encourages the students to also take a stance and advocate for their perspectives in a research-grounded manner, important competencies like understanding other perspectives better to develop elaborated arguments can evolve and be fostered along the way.

Transdisciplinarity has also been pivotal in shaping the learning environment, exposing students to a wide range of perspectives from societal actors in South Africa, practitioners in the field, and researchers as well as experts in various disciplines (agroecology, science communication, design thinking). This diverse interaction has deepened their understanding of the interconnections between ecological, social, and economic systems, encouraging a more holistic and critical approach to problem-solving within agroecological transitions.

Challenges and ways forward

However, challenges remain. Time constraints and the need for effective online collaboration have posed difficulties. While digital tools like Zoom, WhatsApp, and Miro allowed for continued communication and collaboration, the absence of in-person interaction sometimes hindered deeper engagement. Increasing the opportunities for face-to-face collaboration could have enhanced the learning experience.

Additionally, the course has only 3 ECTS, and if we were to ask students to dive appropriately into the topic, we would need a higher time allocation and thus credits compensation. Mobilizing the experts, practitioners, and users of the science communication toolkit has also been challenging, as we want as much iteration and feedback on the prototyping phase as possible to make the product usable. We know that grasping the attention of people working in the field daily might be challenging.

Despite these obstacles, the course adapted successfully, maintaining its focus on meaningful learning experiences. At the same time, we plant seeds of knowledge and critical thinking in students' minds without controlling when or how they will harvest the benefits of their intellectual growth. The poetic of growth is not linear. In the end, we see this work as just one of the many teaching practices they will encounter throughout their learning journey.

Conclusion

In summary, the 'Agroecologist Without Borders' course has effectively integrated Design Thinking into its project-based learning framework, equipping students with the skills and insights necessary to tackle complex agroecological challenges. The course's emphasis on stakeholder engagement, transdisciplinary collaboration, and participatory knowledge creation has enriched the educational experience and prepared students to be impactful contributors to the field of agroecology.

This innovative approach underscores the importance of fostering both critical and creative thinking in agroecological education. The dynamic and supportive learning environment has empowered students to navigate the complexities of agroecological systems, thereby positioning them to contribute meaningfully to the transformation of food systems. Despite the challenges posed by the transnational nature of the course and the necessity for online collaboration, the course has demonstrated resilience and adaptability. It stands as a model for future iterations, offering a pathway to continued evolution and relevance in response to emerging global challenges.

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Integrating stakeholders in project-based transdisciplinary teaching and learning – the case of 'Tackling Environmental Problems'

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Abstract

In this reflection on a teaching practice, we present how we implement project-based transdisciplinary teaching and learning in the Bachelor of Environmental Science (hereafter BSc) course 'Tackling Environmental Problems' ('Umweltproblemlösen' in German, abbreviated as UPL hereafter) at ETH Zurich. First, we focus on the question of how stakeholders are involved in transdisciplinary higher education courses. Then, we present which stakeholders we involve in UPL and which roles they take. A (non-exhaustive) literature review of transdisciplinary courses in other institutions has shown that it is often not explicitly described which stakeholders, and especially in which roles, they are involved in a project-based transdisciplinary course. In UPL, we distinguish between stakeholders at the course level of the case study and stakeholders at the project level who are approached by the students for development of their sustainability projects. Finally, we discuss why we integrate stakeholders in our course and link this to the development of transdisciplinary competences. We conclude with a reflection on the challenges and opportunities of the stakeholders, lecturers and students, as well as experiences, reflections, and feedback from eight years of running this course.

Introduction

For many environmental issues, students who enter the Bachelor of Environmental Sciences at ETH Zurich might be convinced that 1) the problems are clearly defined, 2) the solutions ready to be implemented, and 3) the missing link is (political) will. Our goal is to fundamentally challenge these assumptions. To do so, we use the concept of wicked problems as the starting point in our course 'Tackling Environmental Problems' (UPL). According to Rittel and Webber (1973), wicked problems lack a clear definition and have multiple reasons. Therefore consequently, they do not offer a unique solution, but rather multiple solutions. In contrast, the way a problem is described already defines the space of possible solutions. Furthermore, the problem may appear differently to various stakeholders involved, some may not see a problem at all, whereas for others an action is required immediately.

We let students experience the diverse perceptions of wicked problems by including stakeholders from diverse societal sectors throughout our course. We involve relevant stakeholders from early on in identifying and framing specific problems, as experts for local knowledge during problem analysis and when students develop and test solutions. Students thus experience the wickedness of problems through their own interactions with stakeholders from a specific case area.

At the beginning of their studies, students often encounter disciplinary foundations. It is crucial for them to understand from the outset that today's complex challenges cannot be solved by a single discipline alone. Instead, they require the collaboration of multiple disciplines, as well as knowledge and perspectives from practical experience.

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UPL is a first-year course in the Bachelor of Environmental Sciences at ETH Zurich. According to the study guide, *'we equip the students with the ability to tackle today's environmental problems at local, regional, and global levels. The students will learn to analyse environmentally relevant issues using scientific methods, develop solutions, and evaluate them'* (translated from Departement Umweltnaturwissenschaften, 2024, p. ii). 'Tackling Environmental Problems' aims to bridge the gap between science and practice while fostering transdisciplinary competences among students. These include for instance method-specific competences like problem solving and imagining solutions and their consequences, social competences like communication and teamwork as well as personal competences like systems thinking and reflection. Through a project-based and self-organised teaching format, students are confronted with real-world problems and learn how they can contribute to their solutions.

This manuscript addresses the question of which stakeholders and how they are involved in transdisciplinary higher education courses. First, we describe general reasons for involving stakeholders in transdisciplinary courses. We provide examples of other courses and institutions as well. Then we outline why we involve stakeholders in our course. We are convinced that by directly applying learned methods in a real-world context and with directly affected stakeholders, students are much more likely to acquire new competencies than if they were to learn them purely theoretically. To cover different perspectives and local knowledge, we involved stakeholders who performed different roles. Depending on the course phase, we lecturers work with an advisory group as well as practical experts. Additionally, students independently contact other societal stakeholders relevant to their respective projects. We explain how collaboration and exchange with stakeholders helps students to develop transdisciplinary competences. Finally, we discuss the challenges and opportunities that arise in this process for stakeholders, lecturers and students.

Our work is based on a non-exhaustive overview review of the literature, previous work and our experiences, reflections and feedback from eight years of running this course.

Stakeholders in transdisciplinary courses

The involvement of stakeholders is a core feature of transdisciplinary research and teaching. They can be involved to fulfil many objectives and principles (Schmidt et al., 2020). In UPL, we mainly focus on the principles 'Improvement of the quality of research' (in our case teaching), and 'Stimulating processes of social learning to better understand and solve the problem' (Schmidt et al., 2020, p.3). The stakeholders offer the diversity of perspectives of those who are concerned by the wicked problem.

The transdisciplinary research process explicitly connects the realm of science with the realm of practice (see Figure 1). *'The transdisciplinary process consists of the stages of framing the problem, analyzing the problem, and exploring the project's impact'* (Pohl et al., 2017, p. 44). Stakeholder groups from society (Figure 2) are integrated either in the realm of science (academia) or practice (administration, business, and civil society). In our manuscript, we have further assigned the stakeholders to the course level or project level. We will discuss this in more detail later.

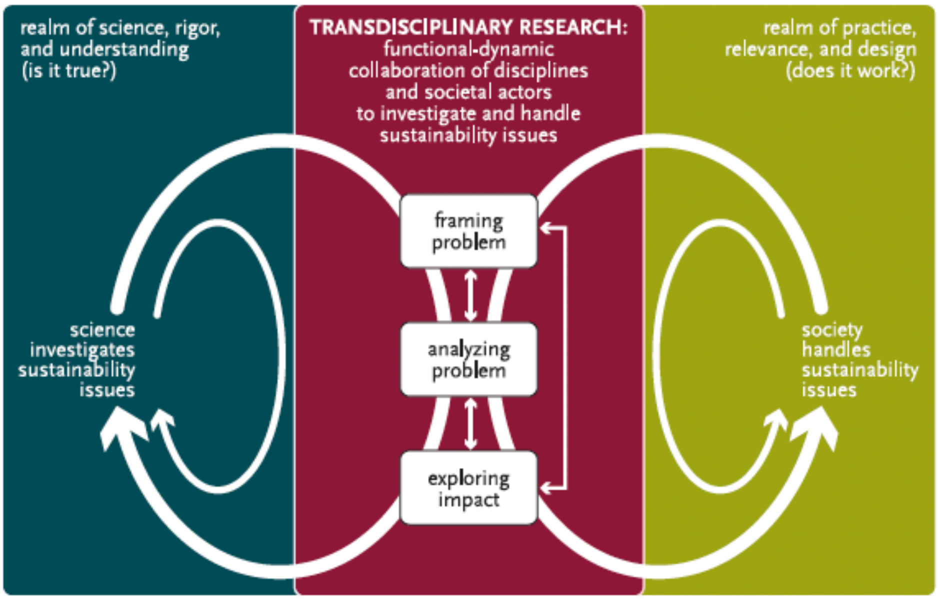

Figure 1: The transdisciplinary research process - Join Problem Framing and Solving between the realm of science and the realm of society as described in Pohl et al., 2017, p. 44.

In our course, we distinguish between four types of stakeholders as described in Figure 2. We have a main partner, an advisory group, practical experts and societal stakeholders. It will be further described below when they appear in the UPL process and what their roles are.

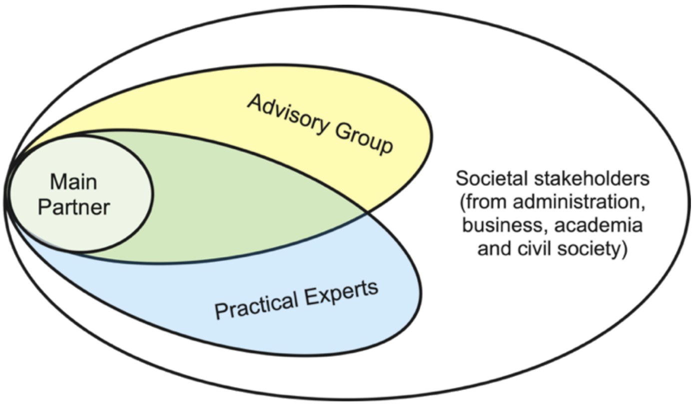

Figure 2: The different types of stakeholders of the BSc course 'Tackling Environmental Problems'.

In our short (and non-exhaustive) review (see Figure 2), we discover that stakeholders are mainly integrated as 'practitioners' in other programmes. This means that the details of the stakeholder engagement are not usually described. There is no or very little distinction between 1) the different types of stakeholders, 2) when they are involved and in which part of the transdisciplinary process, and 3) the role they perform. As explained in our programme, we have four different types of stakeholders who perform different roles at different stages of the transdisciplinary research process.

Name of the Programme	Type Stakeholder	Roles	Institutions	Source
Bachelor of Creative Intelligence and Innovation (BCII)	Industry Partners	- Challenges Provider (co-creation) - Transfer of knowledge and Perspectives	University of Technology, Syndney	Baumber, 2022

Bachelor of Technology and Innovation (BTi)	Industry Partners	- Challenges Provider (co-creation) - Transfer of knowledge and Perspectives	University of Technology, Syndney	Baumber, 2022
Diploma in Innovation (DipInn)	Industry Partners	- Challenges Provider (co-creation) - Transfer of knowledge and Perspectives	University of Technology, Syndney	Baumber, 2022
'The sustainable development indicator exercise (SDIE)', graduate-level seminar	Not specified	- Co-creation	University of Geneva	Balsiger, 2015
'Transformative Innovation Lab', MSc learning course developed and tested at 2 German universities	Local Practice Partners	- Not specified	Not mentioned	Bernert et al., 2022
the 'Sustainability Challenge', a learning environment for Td learning and teaching	Society	- Co-creation - Transfer of knowledge and Perspectives	4 Universities of Vienna (Regional Centre of Expertise on Education for Sustainable Development, which includes City of Vienna, UN EP and others)	Biberhofer & Rammel, 2017
'Transacademic case study'	Community Partners	- Not specified	School of Sustainability at Arizona State University	Brundiers et al., 2010
Certificate Program 'el Mundo - ESD in university level teacher education'	Not specified	- Collaboration	Ludwig-Maximilians-University Munich	Hoiß, 2020
Undergraduate course 'Wicked Problems of Sustainability'	Society	- Co-creation - Transfer of knowledge and Perspectives - Feedback	Grand Valley State University, USA	Lake et al., 2016
'the NYC office of Public Imagination', studio course, Transdisciplinary design MFA Program	Society	- Co-creation	Parsons School of Design, USA	Penin et al., 2015

ETH Certificate of Advanced Studies in Climate Innovation	Society	- Challenges Provider (co-creation) - Transfer of knowledge and Perspectives - Consultation and Feedback	ETH Zurich	Rapo et al., 2024
'Leuphana Semester with opening week', for all first year students	Not specified	- Not specified	Leuphana University Lüneburg	Adomßent, 2022
'Complementary Studies', selected by 2nd to 3rd year students	Not specified	- Not specified	Leuphana University Lüneburg	Adomßent, 2022

Table 1: Transdisciplinary Learning Formats offered at different institutions including types and roles of stakeholder involved (when available). The roles reported are described in Figure 3 (Transfer of Knowledge and Perspectives, Co-Creation, Coaching & Feedback, Consultation, Grading).

The course 'Tackling Environmental Problems'

In UPL, we wish students to experience the process of problem solving by means of a concrete case study. The obligatory course is for first semester students in the Bachelor of Environmental Sciences and lasts a whole year. Around 120 students attend the course. Every year we work on a different sustainability topic in Switzerland, e.g. sustainable water management in the Upper Engadine, regional development in the Jurapark Aargau, or a climate-positive canton of Uri (cp. Pohl et al., 2018; Pohl et al., 2020; USYS-TdLab, 2024). This sustainability topic represents the case study under investigation.

The first semester (UPL I) is about analysing the situation and the case topic. Each case study is divided into five to six sub-analyses. For instance, for the case study Uri, which we worked on in 2023/2024, the aim was to explore how mobility, agriculture, energy, consumption or tourism contribute to a climate positive canton. Four student groups of five to seven members deal with one of the sub-analyses. They carry out a literature search, a stakeholder analysis and gain insights as part of an excursion.

The synthesis week takes place after the first semester. The student groups are reshuffled so that one student from each sub-analysis is represented in a new group. The purpose of the synthesis week is to bring together all the knowledge from the first semester and to make the students experience how it is to be an expert. During this block week, students familiarise themselves with our problem-solving approach – a combination of systems thinking and design thinking (Pohl et al., 2020). They learn to identify stakeholder needs, formulate problems and develop solutions that also have an impact in the overall system.

In the second semester (UPL II), the students independently apply the methods learnt during the synthesis week in sustainability projects they develop themselves. They draw a rich picture, formulate an insight and problem statements, develop a qualitative system model, develop measures, prototype them (Pohl et al., 2020) and present their projects at a public final event, the 'market of measures'. The students follow an iterative process, where the contact with and feedback of stakeholders presents an important part to further develop their projects.
If they wish, they can realise their projects in an optional third semester (UPL III).

We follow ETH's approach to project-based education (cp. PBLabs, 2024). The practice-oriented project approach, where students work in self-organised groups, is an integral component of our course. Particularly in UPL II and UPL III, project work is emphasised. Students learn the methodological and transferable competences we aim to foster through direct application. We, as lecturers and our tutors, act as coaches and support students in their learning processes. When grading groups, we also grade this process and the reflection on it.

Why we integrate stakeholders

UPL aims to bridge the gap between science and practice while fostering transdisciplinary competencies among students. Through a self-organised teaching format, students are confronted with real-world problems and learn how they can contribute to their solutions. In competence-oriented teaching, the focus is not only on imparting knowledge (primarily case-specific, local, and context-related knowledge in our case) but also on developing skills and attitudes. This is achieved through a project-based iterative process of application, practice, and experimentation. In UPL, failure is explicitly allowed and encouraged, if students reflected upon and use it as a learning opportunity for future applications. The emphasis is strongly on 'learning by doing'.

The development of competences in our course is based on the ETH competence framework, which distinguishes between four competence domains: subject-specific competences, method-specific competences, social competences and personal competences (ETH Zurich, 2023). However, this framework does not encompass all the competences we aim to promote in transdisciplinary teaching (see Pearce et al., 2018). Therefore, we have supplemented it as shown in Table 2.

Regarding subject-specific competences, we are not only interested in whether students understand and can apply specific concepts, but also in their ability to apply these concepts in diverse real-world contexts. Among the method-specific competences, problem solving is central to our degree program. In UPL, we also emphasize problem framing, which involves collaboration with others. Consequently, we have included this aspect. Holistic and future-oriented problem solving is also important to us. As this is not covered in the ETH competence framework, we have added the competence 'Imagining solutions and their consequences'. We identify two areas within the social competence of 'communication': firstly, communicating one's own values, and secondly, communicating with stakeholders. In the ETH competence framework, systems thinking is categorized under 'critical thinking'. Given its importance to us, we list it as a separate competence.

In the following Table 2, we describe how the involvement of and exchange with stakeholders supports students in developing these competences.

The competences 'Framing and solving complex problems with others', 'Imagining solutions and their consequences' as well as 'Communicating with others in different contexts' apply to UPL II only, while the others are embedded both in UPL I and UPL II.

Competence domains	Competences in UPL	Supported by interaction with stakeholders	Phase of td research process
Subject-specific competences	Applying concepts in the real world	The application of concepts and methods in the real world requires an exchange with stakeholders. Through their experience, build-on local and practical knowledge, they can judge what works and what not. Students realise how important the knowledge of the local context is. There is no one right solution to wicked problems.	Analysing the problem (Exploring impact)
Method-specific competences	Framing and solving complex problems with others	By talking to stakeholders, students learn about the different needs of the people concerned. Through these different perspectives on an insight, they recognise why a problem can be wicked. Students ask stakeholders for feedback on their initial drafts of solutions and, as the project progresses, more concretely on their prototypes of measures. This feedback from the stakeholders enables the students to recognise whether their measures really contribute to solving a real problem and fulfil the needs of the stakeholders. It helps them to make their ideas implementable. While stakeholders usually have a rather passive role in the development of measures, they are key partners in the facultative project implementation.	Framing the problem Analysing the problem Exploring impact
	Imagining solutions and their consequences	Through the exchange with stakeholders, students can find out whether their skills in developing effective solutions and recognising their potential impacts on the system are also practically applicable.	(Exploring impact)
Social competences	Communicating your own values and communicating with others in different contexts	The worldview of stakeholders can often be diverse. This can help students to question and reflect on their own values. They learn to communicate with different people (from science, practice, administration, business, etc.) at on equal footing and in 'their' respective language.	(Framing the problem) (Analysing the problem)

	Cooperation and teamwork	During UPL, students always work in groups. They reflect on their group collaboration and their work process in a weekly learning journal (with short entries or videos). They define their group ideal, reflect on their individual roles and strengths within the group. They learn to evaluate each other and give constructive feedback. Students develop this competence above all in exchange with their own group. When students develop their projects in UPL II in close collaboration with stakeholders, this level is added once again.	Framing the problem Analysing the problem Exploring impact
Personal competences	Critical thinking Systems thinking	Students develop the ability to distinguish scientific facts from the personal opinions of stakeholders. They must take both into consideration and synthesise different sources in order to develop implementable measures. They must critically evaluate which measures make sense, also with regard to systemic impacts.	(Framing the problem) (Analysing the problem) (Exploring impact)
	Reflecting about self and others	Through the exchange with stakeholders, but also through working in a group, students get to know different points of view. This can help them to reflect on their own views and recognise where their strengths and weaknesses lie. They learn to listen to other people and better understand and accept their perspectives and behaviour.	(Framing the problem) (Exploring impact)

Table 2: Competences in UPL and how the interaction with stakeholders supports their development.

Which stakeholders we integrate and how

The involvement of stakeholders in different phases of the transdisciplinary process and with different roles is a core element of our course. We distinguish between two levels: the course level and the project level. With reference to Figure 3, the course level (left) is therefore about the respective sustainability case study as such, while the project level (right) concerns the individual student group projects. The figure links these two levels with the transdisciplinary research process in the centre. In the following, we explain how this works in detail.

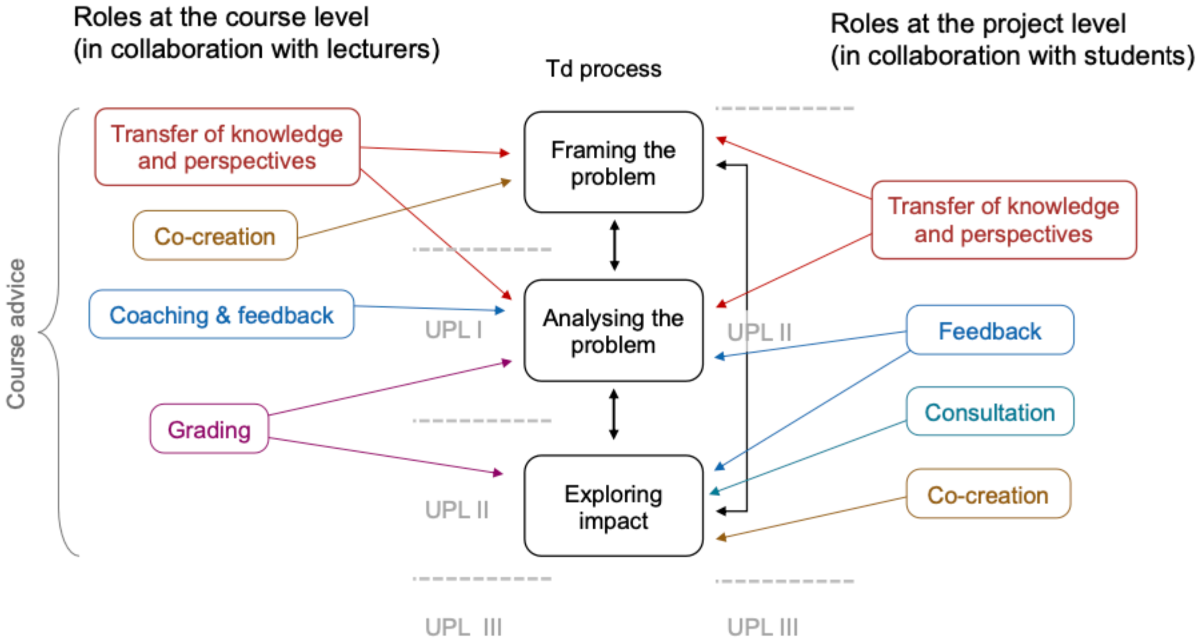

Figure 3: The roles of stakeholders in 'Tackling Environmental Problems' (UPL) in the transdisciplinary research process (own figure based on Pohl et al., 2017, p. 44).

Stakeholders' roles at the course level

Every year, we work with an advisory group. Half a year before the first semester starts, we identify a topic as well as a main partner from a Swiss region. This can be a community mayor, a head of a cantonal office, an employee of a research institution or a company. Together with them, we consider an initial draft of the case topic and which other people we can ask to join our advisory group. Besides the main partner, the group consists of stakeholders of the course (lecturers and two representatives each of the students and tutors) and stakeholders of the respective case (representing administration, business, academia and civil society). We always choose stakeholders from these four areas as we believe they represent important areas of society and come with different perceptions of, and interest in, the topic. In order to make well-founded decisions on the case topic and the sub-analyses, it is important for us to incorporate these perspectives right from the beginning. Two representatives of the lecturers, tutors and students complete the advisory group. They ensure that the learning objectives and framework conditions of the course are guaranteed. The tutors and students also make sure that, for example, questions are understandable for future students and tasks are distributed.

In Figure 3, the roles of the course level on the left-hand side relate to the involvement of the advisory group and practical experts. The advisory group has an important role in 'framing the problem'. Together with them we lecturers determine (and co-create) the respective case topic. In this way, we want to ensure that we work on a topic that is of regional relevance and that their different perspectives are considered right from the beginning. The advisory group also proposes the sub-analyses and practical experts to accompany them. This all happens before the start of the first semester. Then during the course (UPL I and UPL II), the stakeholders of the case support the course, are available to the students as a source of information and provide feedback. At the end of the course, they are also involved in grading the student projects, thus assessing ‘the impact’ of the projects. Over the course of a year and a half, we meet five times.

Besides the advisory group there are further practical experts for each of the sub-analyses in the first semester (UPL I). We contact them on the recommendation of the advisory group. These are, for example, a farmer, forest ranger or representatives of regional, communal or cantonal offices, energy providers or companies. They contribute their specific regional expertise to the formulation of the sub-analyses and respective research questions. Furthermore, they give a short introductory lecture for the students on their sub-analysis topic, meet once with their four student groups for a feedback discussion and read and assess the student reports at the end of the semester. Thus, they are less concerned with a joint problem framing but more with transferring case knowledge and providing feedback in order to support students in ‘analysing the problem’.

At the course level, i.e. the stakeholders of the respective case study of the advisory group and practical experts, we work with a total of eight to ten stakeholders.

Stakeholders’ roles at the project level

In addition to the official stakeholders of the course (case study), who are approached by us lecturers, the students have the task of contacting further stakeholders independently. This takes place during the second semester, when they work on their projects.

At project level, the entire transdisciplinary process takes place in UPL II. In order to ‘frame the problem’, students approach local stakeholders, ask about their knowledge, challenges and individual perspectives. While ‘analysing the problem’, they conduct research, ask for further information and seek feedback on their assumptions. ‘Exploring impact’ refers to the development of proposed solutions and specific measures that are ready for implementation. The students build prototypes of these measures, which they test with stakeholders and obtain feedback on. In addition, some groups also involve stakeholders in an in-depth consultation process and develop and co-create the measures together. The roles of stakeholders are therefore diverse – they contribute local knowledge and needs, provide hands-on feedback, but can also become partners in the implementation of the student projects. In the course of a case study, students contact about 150-200 different stakeholders.

Challenges and opportunities

After eight years of teaching experience in this course, we can report on a variety of challenges and opportunities. These challenges and opportunities are based on our observations and feedback from the advisory group, as well as from the students. During our final meeting with the advisory group, we inquire about their expectations, experiences and challenges. We gather information from the students through their weekly learning journal entries, where they reflect on their work process, as well as through their individual reflection reports at the end of each semester. Finally, we collect information through the responses during oral exams where the students apply and reflect on what they have learned. Tabl summarises the key challenges and opportunities for stakeholders, lecturers and students in our course, which we address in more detail below.

	Challenges	Opportunities
Stakeholders (incl. members of the advisory group and practical experts)	- Resources (time commitment). - Organising their professional life with course dates and activities. - Possible lack of experience in grading students' work.	- Sharing their local knowledge with students. - Their concerns will be heard. - Gaining new and fresh perspectives from students for problems and possible solutions. - Networking opportunities with other stakeholders and lecturers.
Students	- Identifying relevant stakeholders and establish contacts with them. - Coordination of stakeholder contacts. - Understanding and being able to assess the needs of stakeholders in the overall system. - Dealing with diverse perspectives and sometimes contradictory information.	- Being forced to get out of the university bubble. - Gaining a more comprehensive understanding of specific local sustainability issues. - Experimenting and learning by doing. - Being able to implement their project ideas.
Lecturers	- Resources (high time commitment). - Finding a new case topic and new motivated stakeholders every year. - Coordinating between lecturers, tutors, students and stakeholders.	- Being forced to get out of the university bubble. - Gaining a more comprehensive understanding of specific local sustainability issues. - Having the possibility to realise our transdisciplinary learning objectives. - Networking with regional stakeholders.

Table 3: Overview of challenges and opportunities of integrating stakeholders.

For stakeholders, a challenge is how they can organize themselves professionally to align with our course dates. The members of the advisory group and the practical experts are also involved in the grading. Initially, this responsibility can be quite daunting, and it is difficult for them to estimate the performance level expected from first-semester students. However, with the help of clear assessment criteria and our advice, this has never actually been a problem. Especially when comparing multiple groups they evaluate, they can accurately assess their performances. However, we also adjust their grades, in case they are much lower or higher than the grades given by other stakeholders. Though we never change how they grade the groups relative to each other. The adjustment is to avoid students feeling unfairly treated. The students' inquiries can also be challenging for stakeholders – whether due to the sheer quantity or because they are too general or too detailed.

The greatest challenge for students is in UPL II to first identify the relevant stakeholders, understand their needs, relate these to the overall system of their project and then establish successful contact with them. When they succeed in this, receive helpful responses, and encounter interest and support, it shows them that they have identified a real demand. This helps them to make their project more concrete and often provides significant motivation. On the other hand, it is incredibly frustrating when they do not receive any feedback. However, this is a translation of working with real-world case studies. Students must learn how to formulate their inquiries in a way so that they receive responses that are helpful to them. As all students together can easily contact 200 stakeholders during their project development in the second semester and we want to avoid one stakeholder being contacted by ten different students (and possibly being overwhelmed as a result), the students must coordinate their contacts. One student is responsible for one stakeholder at a time and forwards enquiries from other student groups to him or her collectively. However, this also means that students are not completely free in their requests, have to coordinate well and take other groups into consideration. This can certainly delay their own process. The contacts are entered transparently in a table.

In addition, students are confronted with contradictory information and opinions. For example, they might get different feedback on their work from lecturers and practical experts, as they have different requirements or prioritise certain aspects differently despite having the same assessment criteria. Students also sometimes find information in the literature that does not match the statements of stakeholders. Or stakeholders have contradictory opinions about their projects - some think it's great, some perhaps unnecessary.

Even if students are given a comprehensive assignment for each semester, it is a challenge for them to imagine the end product. Dealing with this uncertainty and learning how to cope with it is a challenge for many.

For us lecturers, the high time commitment is a challenge. Each year, we develop a new case topic in collaboration with a new main partner, a new advisory group and new practical experts. This process starts practically with the question of whom we can contact for collaboration and usually requires several emails and phone calls to convince people to participate in our course. The total time commitment is approximately 50 hours for the advisory group and 35 hours for the practical experts. Although we often encounter interest, the time commitment, which we communicate transparently from the beginning, should not be underestimated. Subsequently, it takes time to build trust and a shared understanding of the course's objectives. Dates and tasks need to be communicated and coordinated. Meetings always take place in the respective case region to show our interest in the topic and the stakeholders. This is well appreciated. As our course involves many different aspects (such as introductory lectures, delivery of milestones, feedback to student groups, optional workshops, an excursion or final events) and groups of people (stakeholders, lecturer's team, tutors and students), coordination and a consistent flow of information between them should not be underestimated. One of our lecturers is responsible for this.

In addition to the challenges, there are also various opportunities. Many stakeholders enjoy sharing their knowledge with young students. They appreciate it when their concerns are taken seriously and met with interest. Many are also happy to participate in our excursion, where they can introduce students to their expertise and everyday life. They value the fresh perspective students bring to problems, the diverse ideas for solutions, and especially when measures are implemented. Another aspect is the opportunity for networking. Even though many stakeholders often already know each other, the course and student projects continually create new contacts or provide the chance to discuss controversial views in a neutral context. Contacts with stakeholders are also of interest to lecturers. For example, a further research project for a real-world lab emerged from the collaboration in the advisory group (Department of Environmental Systems Science, 2022).

The exchange with stakeholders enables both students and lecturers to gain a deeper and more comprehensive understanding of specific sustainability issues. We step out of our higher education bubble and learn about diverse regions and what concerns the people there. Students can experiment with applying their theoretical and methodological knowledge in a real-world context and understand what it takes to solve wicked problems. While many courses end with the development of solutions, students here have the opportunity to implement their measures in an optional third semester. Even if only around 10% do this, the offer is important and was introduced at the request of former students. This course gives us lecturers the opportunity to apply our didactic principles and transdisciplinary learning objectives. We contribute to opening up the universities and taking up concerns from society. In addition, networking with local stakeholders is a valuable side effect.

Conclusions

Dealing with wicked problems in the real world requires an iterative and participative approach of practicing and experimenting. With this teaching practice, we aim to contribute to the current literature by clarifying the roles and involvement of stakeholders. We do this by illustrating the exact process of how, why and which stakeholders we involve in our transdisciplinary teaching and learning process. When we compare the roles of stakeholder in UPL (see Figure 3) with the other teaching and learning formats described in Table 1, we can see that the roles they take on are more diverse in UPL. The international examples from the literature illustrate that the two main roles of the stakeholders are 'transfer of knowledge' and 'co-creation'. In many cases, stakeholders are referred to as partners with whom the content is co-created. Not all authors elaborate on the roles of the stakeholders in their respective programs. In the examples of the University of Technology in Sydney (Baumber, 2022), the co-creation role is also described as a challenge provider. This does not occur in UPL, as the identification of challenges is part of the students' task at the project level (see Figure 3). What is also rarely addressed is the role at the project level of giving students feedback, supporting them in their project development, or actively contributing to finding solutions. No example addresses the involvement of stakeholders in grading at the course level, which is the case in both semesters at UPL.

However, we see differences not only in the roles but also in the types of stakeholders involved and how exactly they are described. For example, industry partners or society are mostly mentioned in the international examples (see Table 1). In UPL, we differentiate between our main partner, the advisory group, practical experts, and further societal stakeholders (see Figure 2). They come from administration, business, academia and civil society to reflect different perspectives in society.

We are convinced that the exchange with stakeholders and their local knowledge, expertise and experience is necessary to promote the development of transdisciplinary competences among students. It is important to us that 1) not only the students familiarise themselves with concepts and methods, but 2) that they also apply them in the real world. This is made possible by working on hands-on projects. Setbacks are also part of this learning experience. Dealing constructively with failures and how they can learn from them so to develop their project further is an ability that will also be relevant in later professional life. UPL is all about learning by doing.

Students learn, among other things, how to deal with conflicting views and integrate different perspectives, critical and systemic thinking, self-organised group work and continuous reflection on their own role and the work process. We think that the tasks students need to fulfil and develop over the span of the course should be more robust as they accommodate diverse perspectives. Additionally, the integration of a various set of stakeholders ensures a higher likelihood of implementing the projects developed by the BSc students at a later stage. All parties involved show a higher ownership of the process and outcomes.

In our view, the following success factors are central to the involvement of stakeholders in our course:

- Project-based work in a real-world context.
- Clear and transparent communication about their time commitment and what they can expect.
- Honest interest in the local situation of the stakeholders and joint agreement on topics and research questions.
- Meetings of the advisory group and the final event for the students always take place in the case region. This seems trivial, but for many stakeholders it makes a difference that we lecturers (and students) are travelling to them.

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Digital pedagogy for data-driven unsolicited urban design

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Abstract

As urban environments evolve with increasing complexity, urban planning must adapt by often responding to unsolicited demands rather than to commissioned, structured work. This paper explores the integration of digital tools – including Digital Twins – into the architectural curriculum at ETH Zurich, aiming to bridge the gap between data-driven site analysis and data-driven design. The study focuses on the application of these methods in real-world contexts, such as the Urban Transformation Project Sarajevo, where students from ETH Zurich and the University of Sarajevo applied the acquired knowledge to the development of a new Urban Plan for Sarajevo. The impact of the newly introduced digital pedagogies is investigated within existing lectures and through innovative learning environments, such as hackathons for architects. The outcomes highlight the potential of digital literacy in supporting future urban planners. By introducing digital tools through project-based learning, students were enabled to connect data-driven site analysis with data-driven unsolicited design processes, fostering a more holistic understanding of urban planning.

1 Introduction

1.1 Digital tools for unsolicited architecture

In the 21st century, urban design is increasingly shaped by bottom-up forces rather than top-down commissions. Many urban spaces emerge through market-driven construction, community initiatives, and informal developments - often without direct architectural input. With only 1% of buildings worldwide designed by architects (Brillembourg et al., 2005), architects must adapt to engaging with unsolicited urban demands rather than relying solely on commissioned structured work.

Unsolicited Architecture (Rem et al., 2008) provides a framework for this shift, encouraging architects to identify needs, experiment with new approaches, and communicate with diverse stakeholders. Future urban planners need to be equipped with the skills to navigate this evolving landscape, proactively engaging with urban challenges rather than waiting for formal commissions. This requires not only a shift in mindset but also the informed application of digital tools that support data-driven, adaptive design processes.

With data and open data becoming increasingly accessible, new Digital Tools are gaining popularity and progressively supporting urban planning and unsolicited architecture. GIS (Geographic Information Systems) enables spatial analysis and cross-layered urban insight. Digital Twins , virtual replicas of urban environments, allow architects to simulate and evaluate interventions within complex urban systems and are emerging as valuable support tools, particularly in the context of data- and evidence-based designs. By learning and leveraging these technologies, architects can develop evidence-based proposals that respond to real-world needs, advocate for their implementation, and contribute meaningfully to the future of urban design.

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1.2 Bridging the gap: From data-driven site analysis into data-driven designs

Traditional architectural education often relies on manual workflows, non-automated site analysis, and graphic-based digital design. While this approach develops essential skills, it can be time-consuming, especially for mapping and site analysis over complex large-scale domains, reducing the time available for actual design work. Furthermore, the transition from data-driven site analysis to data-driven design is often challenging due to the complexity of urban environments, where numerous interdependent variables make it difficult to translate insights into actionable design strategies.

To help bridge this educational gap, this study describes how we introduced and taught digital tools that help architecture students support their designs with data-driven evidence, understand both the qualitative and quantitative aspects of urban planning as complementary and synergistic (Kretzer & Walczak, 2021), and visualize results for communication with diverse stakeholders. By equipping students with methods to analyse, interpret, and visualise urban data, we aim to enhance their digital literacy and enable them to develop context-aware, evidence-based urban designs. Ultimately, this approach fosters a more integrated and practical understanding of urban planning, moving beyond hypothetical exercises to real-world applications.

2 Methodology

This contribution reports on how we equipped architecture students with digital tool literacy in the context of a real, project-based learning environment. Two different pathways were designed and tested to address the identified pedagogical gap:

- ETHZ D-ARCH Design Studios, existing courses where students learned to integrate digital tools into their project development.
- The '*Hack Archthon*', a newly developed learning format.

In both cases, as a real, project-based case study, we selected the Urban Transformation Project of Sarajevo (UTPS) (Klumpner's Chair of Architecture and Urban Design, 2024; Walczak, 2024; Walczak & Pagani, 2022).

This four-year collaboration between ETH Zurich (ETHZ), the University of Sarajevo Faculty of Architecture (UNSA), and the Canton of Sarajevo's Institute of Planning and Development aims to modernize urban planning in Sarajevo. The project involves multiple real stakeholders such as decision and policy makers. A key component of UTPS is the development of the first Digital Twin of the Sarajevo Canton (Figure 1), providing a digital decision-making tool for designing the city's future until 2036 through the elaboration of the new Urban Plan for Sarajevo (Walczak & Pelja-Tabori, 2023; Walczak & Pagani, 2025).

Figure 1: Digital Twin of Sarajevo Canton developed at ETHZ for the UTPS project, with traffic simulations in yellow. Credit: V. Desponds (ETHZ Chair of Architecture and Urban Design).

Table 1 provides an overview of the teaching modules where digital tool teaching was implemented. After a two-year development phase, a total of 270 ETHZ D-ARCH and UNSA students participated in the two-year implementation phase.

The methodology was primarily tested within classes developed around UTPS. To assess scalability and transferability, the methodology was also applied in other contexts, including projects related to São Paulo, Brazil, Medellin, Colombia and an elective course on digital urban imaginaries (film making, and urban design with digital modelling, questioning conventional forms of architectural communication). In all cases, digital tool integration was examined within real-world urban planning projects, where collaboration with diverse stakeholders was essential to evaluate the applicability of these methods in project-based environments.

LEARNING MODULE	MODULE CATEGORY	SEMESTER	IMPLEMENTED DIGITAL TOOLS	NUMBER OF STUDENTS
D-ARCH Design Studio City of investigation: Sarajevo *'Igre i Grad – City Games'*	Existing	Spring Semester 2023	3 workshops on Digital Tools (QGIS&GIS, *EnerPol*, Python) Roll-out of *EnerPol* Interface Continuous support of student projects	35
D-ARCH Design Studio City of investigation: Sarajevo *'Next Madrasa – Neighbourhoods of active knowledge'*	Existing	Fall Semester 2023	Workshop on QGIS&GIS *EnerPol* interface Continuous support of student projects	35
Seminar Week Location: Sarajevo *Hack Archthon*	New	Fall Semester 2023	Multiple Digital Tools (Table 2)	25
Workshops with University of Sarajevo (UNSA) students	New	Fall Semester 2023	Multiple Digital Tools (Table 2)	100
Design Studio City of investigation: São Paulo *'Central Park Brâsilandia – Reframing Local Urban Nature'*	Existing	Spring Semester 2024	Workshop on QGIS&GIS Continuous support of student projects	35
Elective Course *'ACTION! On The Filmed City - What Is Not There in Front of Us'*	Existing	Spring Semester 2024	Workshop on Unreal Engine/Twinmotion Continuous support of elective course students	20
Design Studio City of investigation: Medellin *'Urban Culture Infrastructure'*	Existing	Spring Semester 2025	Workshop on QGIS&GIS Continuous support of student projects	20
Total				270

Table 1: Overview of case-study learning modules.

2.1 Digital tools in existing teaching modules

In the first half of the implementation phase, digital tools were introduced within existing teaching modules, specifically the ETHZ D-ARCH Design Studios. The focus was set on two key categories of digital tools:

- GIS software and datasets for 'Site Analysis and Mapping' – Tools that streamline data collection, spatial analysis, and mapping, enabling students to identify unsolicited needs and allocate more time to enrich their design projects.
- Digital Twin simulations for 'Evidence-Based Design' – Tools that allow students to quantify urban dynamics and test different urban scenarios with data-driven simulations, using *EnerPol* as a simulation platform.

EnerPol: An ETHZ simulation framework for Digital Twins

EnerPol is an integrated, bottom-up, agent-based assessment framework for Digital Twins developed at ETHZ. It incorporates agent-based demographic, mobility, energy, and urban planning models and has been extensively used over the past decade to quantitatively assess future urban development scenarios (Pagani et al., 2023; Pagani, 2021; Pagani et al., 2019).

In the context of this study, a custom Application Programming Interface (API) (SwissAI, 2024) was developed to grant students access to the first Digital Twin of Sarajevo. More than 70 accounts were created, allowing students to run GPU-powered agent-based simulations of 3.5 million agents over multiple years. Through these simulations, students could iteratively evaluate different urban planning scenarios and integrate data-driven insights into their project work.

Overview and implementation of digital tools

Table 2 summarizes the digital tools introduced, categorizing them by function and implementation context (existing vs. new teaching modules).

CATEGORY	DIGITAL TOOL	FUNCTION	IMPLEMENTATION
GIS data and database	Open Street Maps (*OSM*) Proprietary GIS data from project partners ETHZ data	Spatial data layers building up Digital Twins (e.g. 3D buildings, zoning plans, roads)	Existing and new modules
GIS search engines	*Overpass Turbo* *Osmium Tool*	Web-based and command line-based tools for querying and extracting data from *Open Street Maps*	Existing and new modules
GIS software	Quantum GIS (*QGIS*) *ArcGIS Pro*	Open-source and commercial software used to visualize, edit, and analyse GIS data	Existing and new modules
Python libraries	*GeoPandas*	Python library for geospatial data handling and analysis	Existing and new modules
Digital Twin simulation framework	*EnerPol*	ETHZ agent-based simulation framework for Digital Twins	Existing and new modules
Architectural software	*Rhinoceros 3D / Grasshopper*	Modelling and node-based programming for 3D geometry editing	Existing and new modules
WebGL libraries	*Deck GL*	WebGL-powered library for high-performance, large-scale data visualization	New modules
Cloud-based mapping platforms	*Mapbox* *Maplibre*	Open-source and commercial platform offering geospatial data visualization on custom maps	New modules
Game engines	*Unreal Engine* *Twinmotion*	Importing GIS data and simulation results for real-time rendering photorealistic 4D environments	New modules

Table 2: Investigated Digital Tools.

The Digital Tools were introduced through a series of in-person workshops held at the beginning of the semester. Ongoing support was provided throughout the semester to students who voluntarily chose to integrate these tools into their projects.

2.2 Digital tools in newly developed teaching modules

In the phase of the project, we brought the project to Sarajevo, where we designed and tested a new teaching format: the *Hack Archthon* – 'Visualizing Digital Urban Planning', a hackathon for architecture students co-organized with the University of Sarajevo (Klumpner's Chair of Architecture and Urban Design, 2023; ETHZ Learning and Teaching Fair 2024, 2024). This intensive, one-week event provided an immersive environment where students could deepen their engagement with data processing, computational workflows, and urban data visualization techniques. The *Hack Archthon* took place in an active workspace, the ETHZ Urban Design Studio in Sarajevo (see Figure 2: 'Urban Design Studio Sarajevo').

ETHZ and UNSA students worked in groups, applying Digital Tools independently while receiving on-site guidance and peer-to-peer support. To structure their learning, students selected one of three dedicated focus groups:

1. Architectural Software, Computer Aided Architectural Design (CAAD)
2. *WebGL* libraries and Cloud-based mapping platforms
3. Game Engines

While still covering data mapping, site analysis, and Digital Twin simulations (as introduced in Section 2.1), the *Hack Archthon* placed a stronger focus on data visualization for the UTPS project. To support this, additional visualization tools (Table 2) were introduced, enabling students to explore state-of-the-art 4D aesthetics and data-driven storytelling. The goal was to enhance the communication of quantitative data and integrate these insights into their qualitative design proposals, ultimately facilitating decision-making within a real-world, multi-stakeholder urban planning process like UTPS.

The emphasis was on collaborative problem-solving, iterative learning, and real-time feedback loops through desk crits. A key pedagogical element was the use of physical models as discussion platforms, bridging physical and virtual realities to enhance spatial understanding and decision-making (see Figure 3).

Figure 2: 'Urban Design Studio Sarajevo' with exhibitions, lectures and events during the Hack Archthon in October 2023.

Figure 3: ETHZ and UNSA students collaborating at a large-scale physical model of Sarajevo in the 'Urban Design Studio Sarajevo' with Digital Twin mobility simulations projected on top.

2.3 Assessment framework for the digital pedagogies

The digital pedagogies introduced in Sections 2.1 and 2.2 are evaluated in Section 3 using a combination of qualitative methods. The assessment focuses on three main components:

1. In-class observations – documenting how students engaged with the digital tools in both existing teaching modules and the *Hack Archthon* setting.
2. Analysis of selected student work – assessing how effectively students integrated digital workflows, balancing qualitative and quantitative approaches. During the *Hack Archthon,* particular attention was given to their ability to apply digital tools in full-stack projects – from data processing to visualization – within the constrained timeframe of the hackathon.
3. Student feedback and lessons learned – following the introduction of digital tools in existing teaching modules, an end-of-semester survey was conducted to understand students' perceptions. Insights from this survey informed the design of the new teaching modules. Additional feedback was collected at the end of these modules to further evaluate their impact.

3 Results

This section presents the outcomes of the implemented digital pedagogy. It begins with observations of student learning across both existing teaching modules (3.1.1) and the newly developed *Hack Archthon* format (3.1.2) and selected student work from the *Hack Archthon* (3.2). This is followed by a summary of student feedback (3.3) and key lessons learned (3.4).

3.1 In-class observations

3.1.1 In-class observations for existing teaching modules

During this first project phase, we observed how students effectively bridged the gap between site analysis and design by integrating digital mapping (GIS) and Digital Twin simulations into their workflow. This approach enabled them to develop a more data-driven and integrated approach to urban planning, by simultaneously streamlining the design workflow.

We made the following key observations:

1. GIS software and datasets enabled faster, collaborative site mapping and analysis:
   - Students quickly learned how to use GIS software and datasets, as the methodology is intuitive for architects and can be readily applied.
   - Students were able to access and integrate GIS data from various sources, including UTPS project partner datasets, as well as collect or generate their own data, using the resources introduced during workshops.
   - Students worked collaboratively by overlaying multiple geo-referenced datasets in GIS, ensuring accurate positioning and scaling of newly created data layers. Unlike traditional CAD-based workflows, which required manual positioning, GIS provided a seamless environment for integrating spatial information, improving efficiency and spatial analysis.
   - The multi-layer GIS approach allowed students to derive spatial and quantitative information. For example, Figure 4 illustrates how students collaboratively overlaid GIS data layers from different sources to 'register the existing' and identify intervention areas. These layers included information about administrative boundaries, infrastructure, nurturing, mobility, economy, dwellings, and relevant point of interests in Canton Sarajevo. The analysis of the overlays and cross-correlations led to new unsolicited spatial interpretations that guided the design decisions of the students.

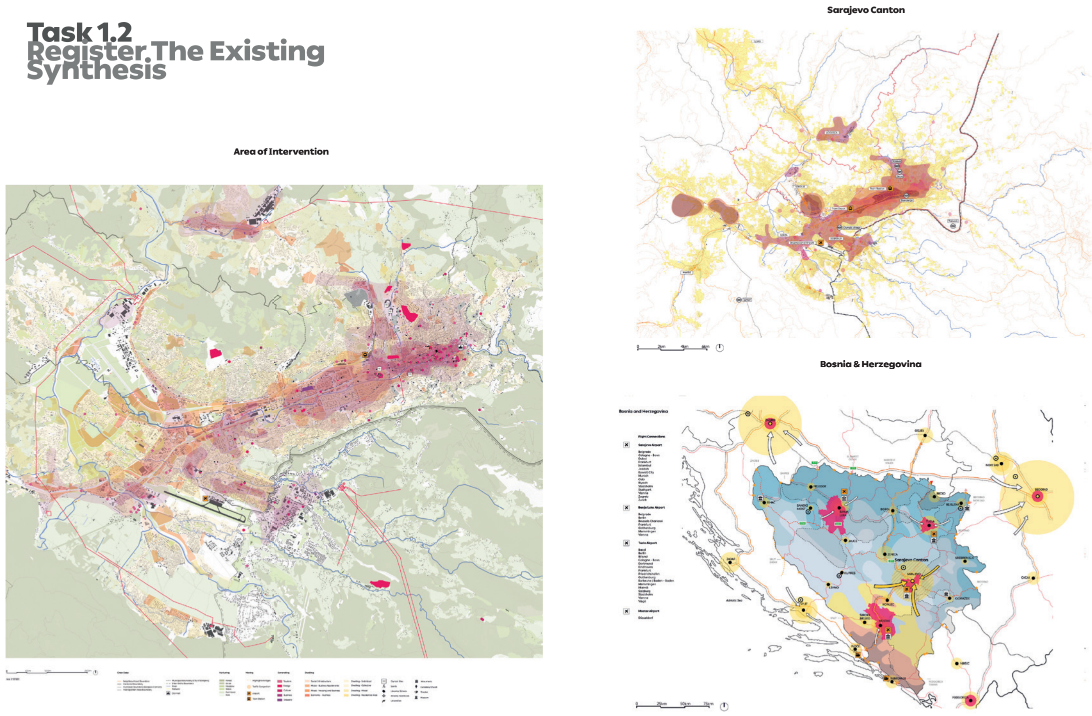

Figure 4: Mapping examples done by the students in the early phases of their projects.

2. Using Digital Twin Simulations (*EnerPol*) to generate quantitative evidence:
   - The introduction of agent-based simulations via the *EnerPol* API allowed students to test urban scenarios iteratively and refine their designs based on real-world, data-driven insights.
   - By modifying zoning plan parameters – such as zone end-uses and construction coefficients – students evaluated how different urban development scenarios influenced population dynamics up to 2036.
   - Figure 5 presents a student's comparison of population density projections for two urban plan designs: the 'Zoning Plan 2023' (baseline scenario, as defined by the UTPS partners) and the student-defined 'Scenario Plan'. Future population distributions were simulated over 5, 10, and 30 years under two migration scenarios:
     - Business as Usual (BU)
     - Stronger Migration (MIG)
   - Based on these results, students adjusted their proposed urban interventions to align with projected population structures.
   - Similar analysis as the one presented in Figure 5 were physically displayed in the Design Studio (e.g., hanging banners), to serve as inspiration, evidence, and discussion platform between peers and project stakeholders.

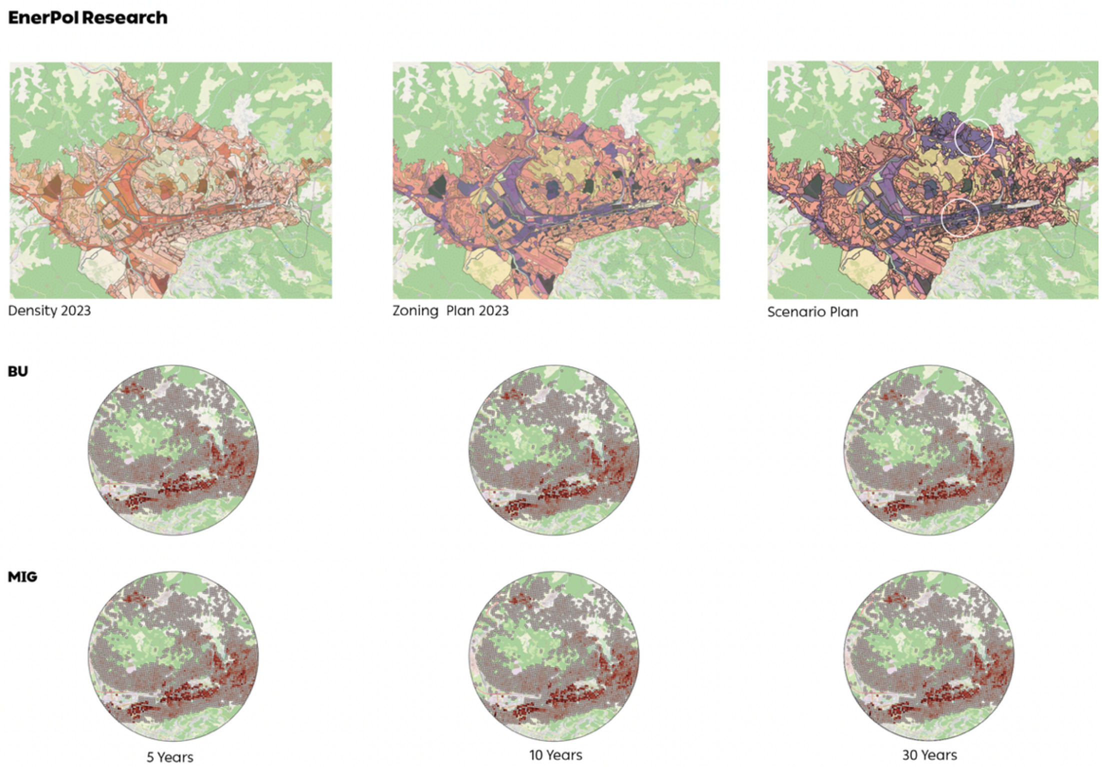

Figure 5: Evidence-based Support Material Generated with EnerPol API. Credit: E. Alili (ETHZ Student).

Through these two points, students were able to identify and respond to urban opportunities with data-driven insights, demonstrating a clear transition from site analysis to informed design decisions. Instead of relying only on qualitative intuition or pre-defined project briefs, students supported their urban planning decisions with quantifiable, evidence-based arguments

Moreover, since GIS and Digital Twin simulations were introduced at the beginning of the semester, students were able to use them throughout their projects, rather than as a late-stage addition. This enabled students to apply the tools before the actual design phase, focusing first on understanding site conditions and identifying unsolicited needs – a crucial aspect of unsolicited architecture.

3.1.2 In-class observations for newly developed teaching modules

The *Hack Archthon* was designed as a testbed for an alternative pedagogical approach, adapting the hackathon format – commonly used in coding and software development – to the architectural context, where such formats are generally not experimented with.

This approach emphasizes rapid problem-solving, prototyping, and team-based iteration under time constraints. By immersing students in a high-intensity, solution-driven setting, we aimed to assess whether this method could enhance students' ability to engage with unsolicited designs in real-world urban projects.

The *Hack Archthon* provided an intensive, dynamic, and collaborative learning environment, simulating real-life urban planning scenarios through a problem-based approach. Unlike the structured format of the Design Studio, where students needed to progress quickly toward a final architectural design and meet strict evaluation criteria, the *Hack Archthon* allowed for a more exploratory approach. Students had the freedom to experiment with different visualization strategies, test alternative data processing methods, and refine their approaches while still receiving direct supervision and feedback.

The *Hack Archthon* enabled students to engage with complex visualization techniques, requiring iterative experimentation. This format allowed them to process and present quantitative data more effectively, ensuring that their outputs were meaningful for real-world multi-stakeholder discussions. While GIS remained a common denominator across all groups, serving as a foundation for spatial analysis and urban mapping, the *Hack Archthon* expanded the digital toolkit, allowing students to integrate advanced digital tools and explore 4D visualization techniques for Digital Twins.

3.2 Analysis of selected student work

The student's work illustrated in Figure 6 presents an effective application of the *Hack Archthon* methodology. This project exemplifies how an architecture student, who typically does not engage with coding or full-stack digital workflows, successfully combined data post-processing, GIS analysis, 3D architectural modelling, and graphic representation into a cohesive urban study. It demonstrates how the *Hack Archthon* provided, within 5 days, an opportunity for architecture students to engage with computational tools and workflows that are rarely part of traditional design curricula.

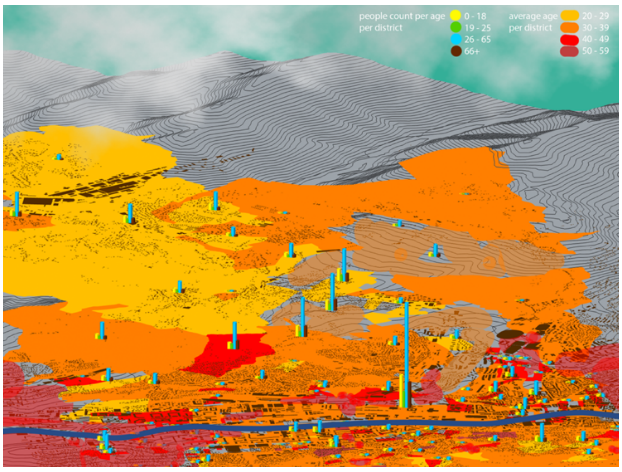

Figure 6: Selection of student work completed during the Hack Archthon. Credit: S. Muntwiler (ETHZ Student).

The workflow followed by the student involved:

- Agent-based Sarajevo Digital Twin simulations (*EnerPol*) to project future age distributions across different city districts, modelling demographic trends over time.
- Post-processing of raw simulation data in *Python* to aggregate and structure results into bar charts
- Visualization through *Grasshopper* (*Rhinoceros 3D*) to condense large datasets into district-averaged bar charts, ensuring clearer interpretation and accessibility for non-technical stakeholders.
- Integration of GIS data to spatially map results onto a digital elevation and building model, layering quantitative insights with qualitative spatial assessments to enhance contextual understanding.
- Refinement of the final representation in Adobe Photoshop, where a colour palette inspired by the Sarajevo Winter Olympics was applied. This choice introduced a cultural and historical reference, making the visualization more intuitive and engaging for multi-stakeholder discussions within UTPS and, more broadly, in urban planning.

Beyond the technical execution, this case highlights how students moved beyond conventional architectural visualization methods to explores multidimensional representations of urban data. By linking digital simulations with contextual storytelling, the project reinforced the potential of visual communication as a tool for interdisciplinary collaboration, demonstrating how architects can play an active role in shaping policy discussions and urban interventions through computational design.

By understanding age distribution patterns at the district level, the student was then able to propose targeted, unsolicited urban design interventions that directly respond to local demographic needs. This data-driven approach aligns with the principles of unsolicited architecture, demonstrating how evidence-based urban planning can enable more precise and responsive strategies – such as designing services and infrastructure tailored to specific age groups and improving decision-making processes in policy and urban governance.

3.3 Student feedback

To evaluate the impact of Digital Tools in the Design Studio, an end-of-semester survey was conducted. The goal was to assess student engagement, perceived usefulness, and challenges, informing the second phase of the project (Section 2.2). Selected survey results are presented in Figures A1 and A2 in the Appendix.

The survey yielded the following key findings:

- GIS data, particularly QGIS and GIS search engines, were highly valued as support tools, with students rating their usefulness at 3.86 out of 5.
- Most students had limited prior experience with Digital Tools, yet we observed that they quickly adapted to GIS-based methodologies and effectively integrated them into their projects likely due to architects' natural affinity for spatial analysis software (Figure A1).
- Among the tools, QGIS/GIS were found to be the most useful. On the other hand, *Python* and *EnerPol* were recognized for their potential in urban planning but perceived as challenging due to limited support, the large group setting, and the semester's tight schedule.
- While students appreciated the introduction of Digital Tools, they also believe that their full potential could only be realized through a dedicated teaching format (Figure A2).

Following the feedback collected through the end-of-semester survey, we identified the need to further experiment with pedagogical formats that encourage students to engage with digital workflows in a more collaborative and intensive way. Therefore, in the second part of the implementation phase, we experimented with a new teaching format (the *Hack Archthon*) to further address the gaps from data-driven site analysis to data-driven design that were not fully bridged in the Design Studios, mostly due to time constraints.

During the evaluation phase of the *Hack Archthon,* we collected student feedback such as:

- *'The Hack Archthon showed me the value of combining different software tools to get the best results.'*
- *'It was a great opportunity to experiment with different media and programs.'*

These reflections underline two key aspects:

- Integration of digital tools: students recognized the importance of combining multiple software tools rather than working in isolated platforms. The freedom to experiment with GIS, *Python*, *Grasshopper*, and visualization tools helped them adapt workflows to real-world urban challenges.
- Increased confidence in computational design: many students had little prior experience with coding or data-driven workflows, yet within five days, they applied full-stack digital methods.

Additionally, students expressed positive feedback on the *Hack Archthon's* structure and setting, thanks to:

- Peer-to-peer learning – The collaborative format allowed students to support each other while navigating new tools, while the exchange with UNSA students provided local insights, reinforcing the value of blending computational analysis with contextual knowledge.

- Creative workspace – The ETHZ Urban Design Studio in Sarajevo functioned simultaneously as a workspace, exhibition venue, and event space, fostering creativity and interdisciplinary collaboration.
- Immersive urban experience – Hosting the *Hack Archthon* in an unfamiliar city complemented digital workflows with site visits and local stakeholders, enhancing students' understanding of real-world urban conditions.

3.4 Lessons learned from student feedback

While the integration of GIS data and GIS-related software and Digital Twin simulations in the Design Studios helped students engage with data-driven design, two aspects still required further development:

1. Extracting meaningful design-relevant insights requires familiarity with data processing tools (such as *Python* or *MS Excel*) to aggregate large datasets into specific design metrics.
2. Effective data visualization is essential for presenting findings in a format that is accessible to multiple stakeholders, including planners, policymakers, and the wider community. Without clear visual representation, the impact of data-driven design remains limited.

Based on this feedback, two key adjustments were made:

- GIS and GIS-related software tutorials will be further integrated into future Design Studios and learning modules.
- A newly developed learning format, structured as a *Hackathon*-style Seminar Week, was offered to provide structured, hands-on training for more complex tools such as *Python* and *EnerPol*, and to set a stronger focus on data visualization for the UTPS project.

4 Conclusions

This paper explored how to enable architecture students to connect data-driven analysis with data-driven unsolicited design. A digital pedagogy was developed and experimented in a project-based learning environment.

This paper demonstrated that introducing Digital Tools through project-based learning is effective in enabling architecture students to bridge data-driven analysis with data-driven unsolicited design, fostering a holistic approach to urban planning. Through the Design Studios and *Hack Archthon*, students engaged with GIS, Digital Twin simulations, and visualization techniques, gaining experience in analysing, interpreting, and applying urban data in the context of a real-world project.

In-class observations, analysis of student work, and feedback evaluation, confirmed that this pedagogical approach enhanced digital literacy and equipped students with the necessary tools to:

- Identify and develop data-driven urban design proposals, integrating quantitative insights with qualitative design approaches in a streamlined manner.
- Carry out full-stack projects, from simulations and data processing to visualisation, within a short time frame.
- Improve their ability to communicate data-driven unsolicited designs to decision makers through advanced visualisation techniques.
- Break software silos by combining multiple tools (GIS, Python, Rhino, Unreal Engine) rather than working within isolated platform.

Digital Tools shall be introduced at the beginning of the semester, ensuring they can be effectively integrated within the time constraints of the Design Studio format. We found GIS and GIS-related software particularly well-suited for this purpose, as they provide a structured yet flexible framework for urban analysis.

Among the various elements of this study, we recommend hackathons as an alternative but effective learning format. Teaching digital tools through hackathons, such as the *Hack Archthon*, offers architecture students a unique opportunity to:

- Apply their knowledge in real-world settings, ensuring hands-on learning.
- Intense and focused collaboration, fostering creativity, teamwork, and problem-solving skills.
- Engage in interdisciplinary and peer-to-peer learning.

4.1 Summary of accomplishments

The following outcomes were achieved:

- Streamlined mapping exercises: Students effectively integrated GIS data and software into their workflow, allowing for more effective mapping exercises and enhancing their ability to spatially analyse urban contexts. Students learned how to access and retrieve GIS data from governmental and open sources.
- Urban design projects supported with quantitative elements: By incorporating Digital Twin simulations, students were able to enrich their projects with large-scale data-driven insights. This allowed for a more informed approach to urban planning proposals, balancing qualitative design decisions with quantitative evidence, as required in unsolicited urban planning.
- Data-driven visualization techniques: Hands-on work during the *Hack Archthon* enabled students to explore data-driven visualization aesthetics, making their proposals more suitable for multi-stakeholder engagement.
- Increased digital literacy: The project improved the digital literacy of a total of 270 students from D-ARCH by familiarizing them with GIS, agent-based Digital Twins, and various digital visualization tools. This enhanced their technical skill set, preparing them for the increasingly digital landscape of urban planning.
- Cross-institutional collaboration: Students could collaborate in one collective Digital Twin through the proposed methodology. The hybrid digital/physical collaboration between ETHZ students and UNSA students during the *Hack Archthon* fostered meaningful peer-to-peer exchanges. This cross-institutional collaboration enriched the learning experience, exposing students to diverse cultures, perspectives, and approaches.

4.2 Further development needed

While this study focused on practical aspects related to teaching digital tools and assessing their integration into student workflows, future research should analyse how students apply the acquired knowledge to support effective decision-making in unsolicited urban design. Investigating how students use computational tools beyond the classroom – particularly in real-world participatory planning processes and stakeholder engagement – will provide deeper insights into the long-term impact of digital pedagogies in architecture education.

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- Seraina Muntwiler
- Esma Alili

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Appendix

End-of-Semester Survey

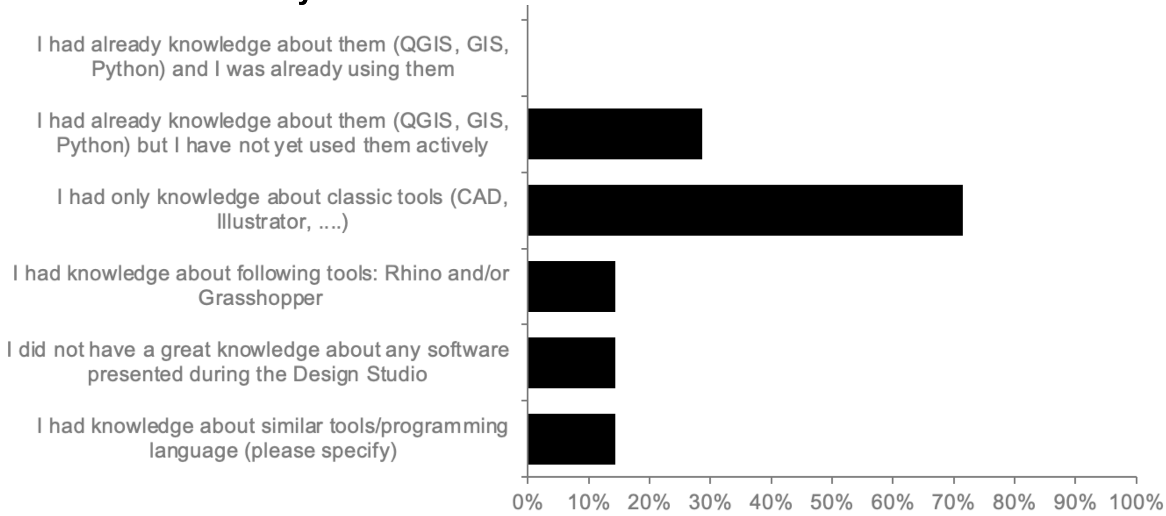

Figure A1: Student answers to the question 'did you have any digital literacy before the Digital Tools tutorials?'.

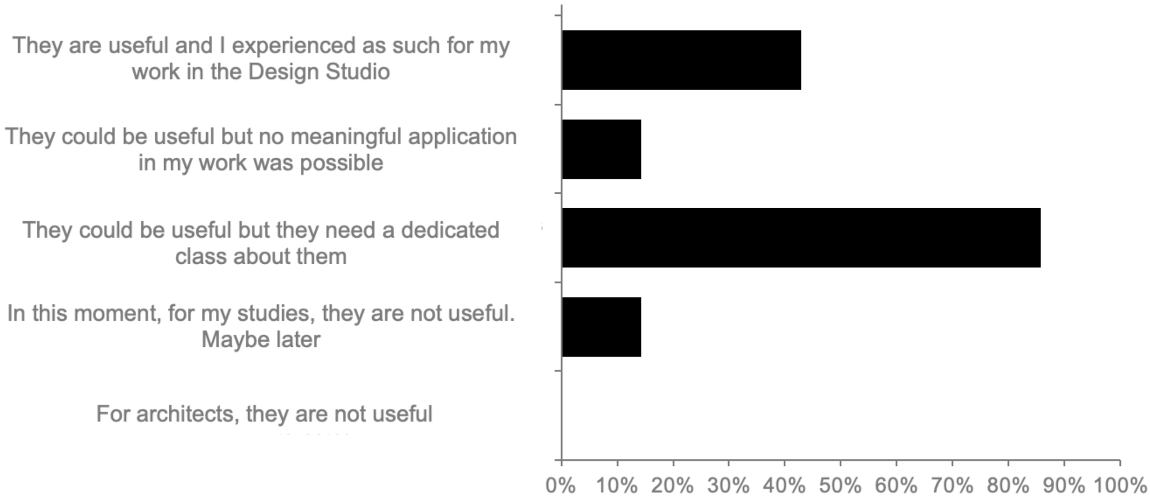

Figure A2: Student answers to the questions 'what do you think about implementing Digital Tools in the Design Studio'.

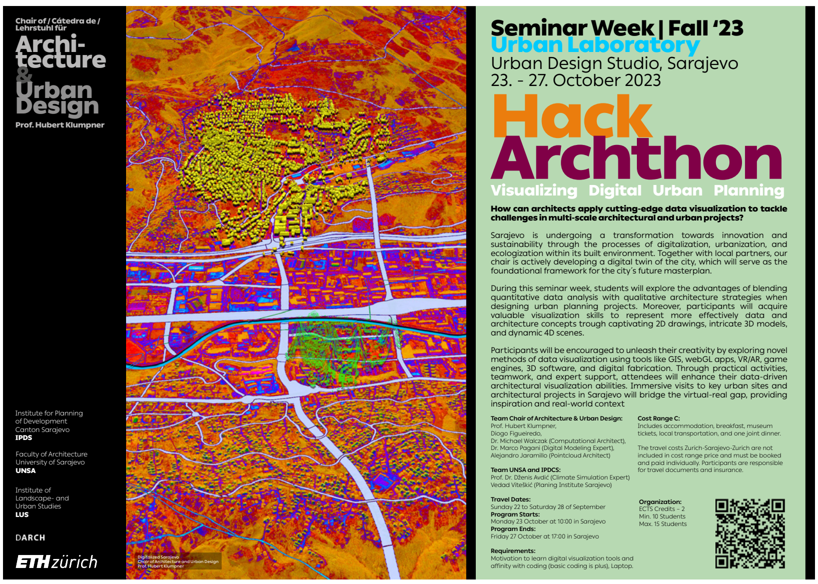

Figure A3: Hack Archthon Banner.

Expanding horizons: The pedagogical benefits of museum visits for engineering students

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Abstract

This paper explores the pedagogical benefits of a museum visit for engineering students. While field trips have proven to be effective tools to improve students' critical thinking, ethical reflection, and cultural awareness, they are still rarely featured in engineering curricula. This paper focuses on a field trip to a museum as part of the course ‘International Engineering: From Hubris to Hope’ at ETH Zürich, where students explored an exhibition addressing colonialism and looted art. We show how this experience bridges the gap between technical knowledge and the complex contexts that engineers must navigate during their career. Combining student questionnaires and reflective reports, we find that students strongly appreciate this type of experiential learning. Moreover, interviews with different stakeholders highlight the importance of field trips in fostering deeper engagement and critical thinking. Overall, our findings suggest that this type of project-based learning can enhance engineering students' preparedness for the ethical and cultural challenges they will encounter in their professional careers.

Introduction

In engineering education, the focus has traditionally been on conveying technical knowledge and honing problem-solving skills through ‘chalk and talk’ (Rugarcia et al., 2000; Shuman et al., 2002; Rosen, 2009). While direct teacher instruction remains an important pedagogical tool, it often falls short of conveying the complexities of the real world. More than ever, engineers must have a well-founded understanding of the cultural and social phenomena with which technology interacts outside the classroom. The course ‘International Engineering: From Hubris to Hope’ at ETH Zürich addresses this need by integrating ethical reflection and cultural understanding in its curriculum through project-based learning. Through debates, interactive panels, and, as highlighted in this paper, a field trip, the course introduces students to issues such as colonialism and cultural appropriation and the implications for students’ careers. This novel approach intends to prepare engineers for working contexts where their decisions and actions can have profound ethical and cultural consequences.

Despite positive trends, most engineering programs lack practical training in skills like critical thinking and cultural empathy. Undergraduate curricula are often saturated with courses focused on direct instruction methods, resulting in few opportunities for learning experiences outside the classroom. For instance, at ETH Zürich, our home institution, students must complete a minimum of 6 ECTS credits in Science in Perspective to ‘understand and critically question the correlations between scientific knowledge, technological innovations, cultural contexts, individuals and society (D-MAVT, 2025).’ These credits account for only 3% of the total required credits.

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Yet, studies show that integrating different teaching methods can significantly enhance learning outcomes for engineers (Lavado-Anguera et al., 2024). Building on these insights, ‘Hubris to Hope’ features a project-based learning approach to get students out of the classroom, into the real world. For last year's iteration of the course, the class visited the exhibition ‘Pathways of Art: How Objects Get to the Museum’ at the Museum Rietberg, where students engaged with exhibits that highlight issues of colonialism and cultural appropriation through the lens of the Benin Bronzes.[2] The project required students, following their visit, to contextualize the topics of art theft and neocolonialism in a worksheet. This reflective exercise aimed to foster a deeper understanding among students of the ongoing consequences of these historical events and their continuing impact on the engineering profession.

Using a mixed-method approach, we aim to answer the following research question: *How can experiential learning methods in the form of a field trip enhance learning outcomes of engineering students and deepen their understanding of complex social issues?* Our methods include questionnaires for students and interviews with both lecturers and the museum's curator to assess the relevance and impact of this type of experiential learning. The goal is to demonstrate the educational value of field trips and their benefits not only for knowledge retention but also regarding social and personal skills. By doing so, we aim to contribute to the ongoing discussion about how to best prepare engineering students for the ethical challenges they will face in their professional lives. Our results indicate that students are not only open to the idea but actively desire more opportunities for project-based, real-world tasks that extend beyond the classroom.

Literature review

Field trips have long been recognized as valuable educational tools (Behrendt & Franklin, 2014; Ramachandiran & Dhanapal, 2016). Underlying this pedagogical tool is the concept of experiential learning, defined as the process ‘whereby knowledge is created through the transformation of experience (Kolb, 2015, p. 49).’ By engaging students in experiences outside the classroom, abstract concepts become tangible and allow students to experience them in the real world. Through learning by doing, bridging the gap between theoretical knowledge and practical application, field trips provide students with hands-on, immersive experiences and have proven to enhance cognitive learning, increase student engagement, and promote personal development (Behrendt & Franklin, 2014; Falk & Balling, 1982).

Only a few studies have evaluated the benefits of field trips on engineering students' learning outcome. Those who did focused mostly on their impact on knowledge retention and practical application. For instance, evaluating the benefits of field trips in construction management courses, Salman (2023) has shown that they provide tactile experiences and real-time professional interactions, which are crucial for a comprehensive learning experience. In another study including industrial engineering students, Townsend and Urbanic (2013) show that field trips result in high student engagement, deep learning (e.g., 42% of the students noticed significant change in their attitudes and beliefs about manufacturing) and the improved ability to relate personal experiences to the field trip.

However, while these studies highlight the benefits of field trips, they do not address to which extent field trips encourage ethical reflection. Although students may internalize some ethical considerations through immersive and emotional learning, understanding how these ethical reflections arise and can be actively encouraged is important. As mentioned earlier, graduates entering international work environments are likely to encounter issues such as white saviorism and cultural appropriation at some point in their career. Being able to critically assess these situations plays a significant role in addressing and changing the underlying mechanisms.

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[2] These plaques and sculptures, generally known as the Benin Bronzes, were made by the Edo people of the Kingdom of Benin, located in modern-day Nigeria (Kiwara-Wilson, 2012). Looted by British forces in 1897, the Bronzes are celebrated for their historical significance and representation of Benin's rich cultural heritage.

Research on how museum visits promote ethical reflections in university students is limited, but insights from lower grades provide some understanding. In their large-scale study, where the randomly assigned treatment consisted of a one-hour museum tour, Green et al. (2014) find that students in the treatment group improved their critical thinking by an average of 9 percent of a standard deviation compared to the control group, operationalizing critical thinking as ability to interpret works and their historical context.

Although their focuses on critical thinking regarding art and its historical context, it opens the door to exploring how museum visits can also promote ethical reflections in visitors. The concept of historical empathy helps to understand some of the underlying mechanisms. Defined as 'the process of students' cognitive and affective engagement with historical figures to better understand and contextualize their lived experiences, decisions, or actions', historical empathy is a key driver behind ethical reflection (Endacott & Brooks, 2013, p. 41). Studying an exhibition on children living through World War II, Savenije and De Bruin (2017) find that even though visiting students did not have a personal connection to these historical events, most were emotionally engaged through the display of objects and the exhibition's focus on personal stories. Smith (2016) observed similar outcomes, with students showing emotional engagement after visiting an exhibition on the British slave trade.

Gammon (2003) provides further insights in his guide 'Assessing Learning in Museum Environments', detailing the learning processes that occur during a museum visit. He identifies five indicators: cognitive, affective, skill-based, social, and personal learning. Cognitive learning involves visitors consolidating their knowledge and connecting it with experiences or knowledge from other areas. This is a key reason why museum visits are part of the 'Hubris to Hope' curriculum. Affective learning, in turn, is closely related to historical empathy. Exhibits and interactive elements challenge visitors' beliefs, fostering empathy or at least an understanding of different perspectives and values. A museum visit is also a social experience. Students get to know each other better and interact with lecturers outside the classroom, which can lead to more cooperation. Finally, the field trip equips students with new skills. The assignment, in our case a report on the experience, is designed to enhance their critical reflection and writing skills, boosting self-efficacy and personal learning as described by Gammon (2003).

Against this backdrop, our paper seeks to explore how a museum visit can promote not only cognitive learning but actively encourage critical thinking and ethical reflection for engineering students. By involving them in immersive and interactive tasks during the trip, this paper aims to provide new insights into leveraging the educational impact of field trips when it comes to preparing future engineers for the ethical and practical challenges they will face in their careers.

Case study: Field trip to Museum Rietberg

The course 'International Engineering: From Hubris to Hope' offers a novel approach to engineering education by combining technical knowledge with ethical reflection. It challenges students, mostly from engineering backgrounds, to think about the broader impact of their work in a global context, especially regarding the ethical responsibilities that come with engineering in a connected world. The course focuses on understanding historical and cultural contexts and reflects on the engineering profession through a global and sociopolitical perspective.

Project-based learning as a pillar of the course

The course aims to promote ethical reflection through several project-based learning approaches, such as debates, flipped classrooms and student presentations. For example, students are asked to find out how to apply for an engineering degree at an African university and share their experience in a presentation with the class. The goal of this hands-on learning approach is to let students experience firsthand the bureaucratic obstacles often encountered when applying for programs or grants. In another assignment, students chose a Sustainable

Development Goal (SDG) and, using a flipped classroom format, presented the flaws and challenges in measuring their selected indicator.

A museum field trip is another project-based component of the course. The city of Zurich hosts several museums that offer exhibitions on course-relevant concepts such as decolonization or the exploitation of natural resources. The Museum Rietberg is known for its collection of art and artifacts from different centuries and regions around the world. Its exhibitions often raise important questions about the origins of the displayed items, many of which are linked to histories of colonialism and cultural appropriation. The museum's 'Pathways of Art: How Objects Get to the Museum' exhibition, along with its visual storage collection, were the focus of the students' visit (Museum Rietberg, 2024). These exhibitions provide a valuable context for students to engage with the ethical dilemmas related to the acquisition and display of cultural artifacts, encouraging them to critically examine Switzerland's role in colonial history and its ongoing impact on global power structures.

Assignment to encourage reflection during field trip

To deepen the student's engagement with the ethical questions raised by the museum's collection, we gave students an assignment prompting them to reflect on their experience. The assignment had two parts, each requiring students to engage critically with the exhibited objects and how they are presented.

In the first part, students chose three objects from different stations within the exhibition. They had to give a brief description of each object, including its history, and consider how both the collectors and creators were represented in the museum's narrative. Students were encouraged to critique the museum's role in acquiring these items, questioning whether the displays accurately and ethically told the story of their acquisition. They also had to identify any missing information and suggest improvements, such as changes to the display text or even the relocation of the objects. Importantly, students were asked to consider whether the objects should be returned to their places of origin.

The second part of the assignment focused on a culturally or religiously significant item from the museum's visual storage collection. Students had to describe how the item was displayed and evaluate whether the display increased or decreased its significance. They reflected on how the original owner or creator might feel about the current display and proposed alternative display methods or ways to return the item to ensure a more just presentation.

Methods

We evaluated the impact and potential benefits of this assignment using a three-step process. First, we asked students to complete a questionnaire that included a mix of multiple-choice and open-ended questions, along with demographic information such as age, academic background, and previous experience. This helped us understand the impact of the field trip on them. Additionally, we wanted to see how students' perceptions of the assignment would change if they knew their reports would be shared with the museum. We asked whether they felt they would have gained something from such an interaction and how they might have approached the assignment differently. Finally, we asked all students if they were willing to share their reports with the museum's directorate. From those who agreed, we collected recurring themes and suggestions for improving the museum's exhibitions, reviewed and corrected them for grammar, and shared a summary with the museum's curator.

Second, we conducted interviews with the two course lecturers to get their views on how effective the field trip was as a teaching tool. These interviews were intended to provide a complete view of how the field trip fits into the overall goals of the course and its impact on student learning. We asked them about their experiences organizing field trips, the impact these trips had on students in their opinion, and their impression on the value of having students submit their reports to the museum.

Third, we conducted an interview with the museum's curator to understand the museum's perspective. We explored her views on the educational value of such field trips, her willingness to engage directly with students, and her openness to including student feedback in the museum's practices as well as read and respond to the student reports. Collecting the museum's feedback was important to know whether it would be possible to make the field trip more interactive by having direct interaction between students and the museum staff during the trip.

Results

Our sample consisted of 23 undergraduate and graduate students, representing around 65% of the course participants. Most of them studied at the Department of Mechanical and Process Engineering (D-MAVT). On average, they were 24.3 years old and had spent 4.1 years at ETH Zurich. As shown in Table A1, students had participated in less than one (0.9) field trip during their studies, highlighting the low prevalence of this pedagogical tool in their study programs.

Overall, students rated the field trip very positively with an average score of 4.04 out of 5 (see Table A2). Most of them found the experience educational and meaningful. The assignment was rated almost equally favorably with an average score of 3.70 out of 5. The slightly lower score might suggest that students appreciated the experience but would have preferred a more structured assignment. On the other hand, the desire for more project-based assignments was strong. The average rating of 4.36 out of 5 underscores the value students place on activities that feel connected to real-world impact.

78% of the students expressed that they would have liked to see the impact of sending their reports to the museum while only 30% believed that they would personally benefit from it. This distinction could highlight the desire to contribute to something meaningful while expecting no to little personal gain from such a contribution. When asked if they would have done something differently if they had known that the reports would be sent to the museum, 65% of the students answered with 'Yes'. With more at stake, this highlights the potential to further encourage students when they know their work will not only be theoretical but also shared with stakeholders or experts. Lastly, almost all students (91%) believed that no specific degree level was necessary for ETH students to engage with external institutions, suggesting confidence in their ability to contribute meaningfully regardless of their academic status.

Below we list a few selected written statements from students to further illustrate their experience and their hopes and expectations for future field trips.[3] Many students expressed a strong desire for experiential learning and opportunities to interact with professionals in their field.

'[Sending our reports] would give our work a purpose and it would make us think more about the way we would write things in the report.'

'[Sending our reports] would provoke a reaction. Even if the museum does not do anything about the criticism, we still learn more about the museum.'

'I wish we had more chances to do projects with stakeholders outside of academia. Where you get real feedback and can work with motivated people.'

These results reflect an enriching experience for most of the students. A large majority rated both the visit and the assignment positively, even though only a few believed their reports would actually make a difference. In this regard, there is still potential to enhance the pedagogical benefits of such trips. As noted in the students' comments, a more tangible output

[3] The feedback was overall very positive. Only one student expressed low confidence in the abilities of students to inform the museum.

could provide a stronger sense of purpose and, consequently, increase student engagement. The survey data confirmed this: nearly two-thirds would have approached the assignment differently if they had known in advance that their work would be shared.

Lecturer observations

To provide more context for the quantitative findings, we interviewed the two course lecturers. Both highlighted the significance of the museum trip, noting that it offered a valuable chance to engage with course material in a more dynamic way outside the classroom. In their opinion, taking students on a field trip fosters different conversations and perspectives, making the learning experience more fun, active and social.

They also observed that students tend to be more engaged and participative not only during but also after a field trip. According to the lecturers, the experience helps students connect theoretical concepts to real-world situations, making their learning more relevant and memorable. In the weeks after the field trip, one lecturer mentioned that students were more likely to bring up examples from the field trip than from the literature during the lectures.

'I find that when you look at their writing and we look at their exams, they draw on those experiences more than they do on the readings.'

Moreover, the lecturers noted that the field trip actively fostered critical thinking. After the trip, students demonstrated a noticeable shift from abstract understanding to using concrete examples in their analyses and critiques. This change was marked by a deeper, more grounded reflection as they began to reflect more on their backgrounds and experiences, often sharing personal stories that enriched class discussions.

There was also a social benefit to the field trip. After the museum visit, social interaction and class dynamics became livelier. The informal setting helped break down barriers between both students and lecturers, fostering a more relaxed and open atmosphere. Students could interact with their lecturers and peers outside the classroom, enhancing the overall learning environment. As one lecturer put it:

'I think the classroom is a limited learning space, and when you go outside the classroom, you open that up. Having a conversation with the students and amongst the students in a different space is also important.'

However, the lecturers also mentioned challenges and improvements needed for future field trips. Both emphasized the importance of a well-structured trip. This resonates with the findings from Lee (2020) who found a positive association between student outcomes and pre-visit preparation and post-visit activities. They considered involving museum staff to enhance the learning experience, though they recognized this might present challenges. One lecturer remarked that while students would likely benefit greatly from such interactions and improve important skills, it would entail extensive planning for the teachers, a challenge also mentioned by Salman (2023).

Museum interview

Lastly, we interviewed the museum’s curator for the Africa and Oceania sections, Michaela Oberhofer, to gain insight into the museum's perspective. Before the interview, we had sent her a curated compilation of student letters. After reviewing them, she acknowledged that while the students clearly demonstrated critical thinking, there was still room for improvement. To close this gap, she suggested a more in-depth exchange, something that was also requested by the students, to make the students’ analysis more substantial. Oberhofer was also open to join the class to discuss the political and ethical challenges surrounding the museum’s collection. Lastly, she proposed a more structured process to the museum visit: Students could first visit the museum at their own pace and write the report based on their visit. Once submitted, the students would participate in a follow-up discussion with museum staff, allowing for deeper reflection and giving students the opportunity to engage in a more comprehensive dialogue about the ethical, political, and cultural considerations behind the museum's practices.

Discussion

Our results show that students appreciate the opportunity to engage with the subject matter through immersive experiences. The survey feedback was overall positive, with students expressing a strong interest for more interactions during the visit. This enthusiasm was echoed in the qualitative feedback, where both lecturers and the museum's curator highlighted the value of these interactions in fostering a deeper understanding of the complex social and cultural issues surrounding the artwork exposed.

The feedback from lecturers reinforced the importance of integrating more immersive experiences into the engineering curriculum. They observed that students became more engaged and demonstrated a deeper level of critical thinking after the museum visit. They also noted that students were more likely to draw on real-life examples in their discussions and assignments, which helped them connect theoretical concepts to tangible experiences. This shift from abstract to concrete thinking is particularly important as engineering students tend to focus on technical problem-solving at the expense of soft skills (Caratozzolo et al., 2019).

Despite the promising results, we acknowledge a few limitations. First, the dataset is small, with responses collected from a limited number of students specific to one course at ETH Zurich. This limits somewhat the generalizability of our findings to other contexts. We suggest that future research should involve a more extensive and diverse group of subjects to explore the opportunities of field trips across a wider range of courses and institutions.

We are also aware that the COVID pandemic made most field visits impossible, resulting in the limited experience of students in this regard. Therefore, our results may not fully represent the broader population of engineering students or other educational settings where field trips are an essential part of the curriculum.

Conclusion

This study aimed to demonstrate that bringing students away from their textbooks into the real-world has the potential to foster critical thinking in engineering students. The positive reception from both students and lecturers underscores the value of the field trip, particularly in fostering deeper learning and ethical, social and cultural understanding. However, the findings also highlight the importance of carefully structuring assignments to ensure they are both impactful and meaningful to students. While this study's scope is limited to one course, the results suggest that integrating more real-world tasks into engineering curricula could better prepare students for the ethical and cultural challenges they will face in their professional lives.

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Declaration of generative AI and AI-assisted technologies: The authors used the below listed AI-based tools. The authors take full responsibility for the content of the publication.

AI Tool	Use Case	Scope	Example Prompt
Microsoft Copilot (through ETH) *Last date of access: 20.02.2025*	Linguistic improvements	Whole paper	'Make this sound more natural.' 'Rephrase this sentence. Give me five alternatives.' 'The wording is off here, the transition between the paragraphs is too rough. Can you give me some leads?' 'Give me ten alternative titles for this one: Beyond the Books: The Pedagogical Benefits of Taking Mechanical Engineers to a Museum'
Perplexity (free tier) *Last date of access: 20.02.2025*	Finding papers	Literature Review	'Studies showing how museum visits encourage ethical reflection in students.'
Scopus AI (through ETH) *Last date of access: 20.02.2025*	Finding papers	Literature Review	'Studies showing how museum visits encourage ethical reflection in students.'

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Appendix

Question	Unit	Average
Age	Years	24.3
Years at ETH	Years	4.1
Number of previous field trips	Field Trips	0.9

Table A1: Survey Demographics.

Question	Unit	Average
How would you rate the visit to the Rietberg Museum as part of the course? (1: I learned nothing, 5: I learned a lot)	Likert	4.04
How would you rate the assignment (report)? (1: I learned nothing, 5: I learned a lot)	Likert	3.70
Would you enjoy more task-based assignments? (1: Not at all, 5: Very much)	Likert	4.36
Would you have liked the potential impact of actually sending the report?	% Yes	78
Would you have profited from the potential impact?	% Yes	30
Would you have done something differently if you had known the reports would be sent during the semester?	% Yes	65
What level of degree do you think is necessary for ETH students to be qualified to engage with members from other institutions/government?	% said no degree	91

Table A2: Survey Responses.

Influence of distractors on student's performance and confidence in single choice quizzes

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Abstract

Single choice questions are a substantial part of exams in various fields, in particular in mathematics. However, few studies have examined how the provided incorrect answer options (the so-called 'distractors') in mathematical questions are affecting the achievement of the students. In this paper we describe a study designed to investigate not only the effect of distractors on the performance, but also which kind of distractors make students uncertain or, on the contrary, lull students into a false sense of security.

Introduction

As the number of students at ETH is increasing year after year, and with it the correction workload, more and more multiple choice questions are being used in examinations to prevent the correction workload from becoming immeasurable. While a lot of time is undeniably saved during correction, the question arises as to whether an exam with single choice questions is just as meaningful as an exam with open-ended questions. In other words, the question arises as to how single choice questions should be designed so that they can capture the students' level of performance as well as possible. As the worked out solution is not recorded in single choice questions, it is not possible to understand the students' thoughts. On the one hand, this makes it difficult to recognize a poorly constructed question. On the other hand, it is all the more important that single choice questions are well thought out so that the examination result is meaningful. There is already a lot of literature on this, e.g. Haladyna (2004), Abramovitz et al. (2005) and Krebs (2019) that also provide examples showing how not to formulate single choice questions. For example, when creating these, care should be taken to ensure that the question is clearly formulated and, in particular, that there are no double negatives. All answer options should also be of a similar length and Hembree (1987) suggests that a number of 3 distractors is best – but this is only backed by references to previous theoretical work, since there were not enough relevant studies in their meta-analysis. Among other things, the literature recommends the use of functioning distractors. This means that incorrect answer options are available for selection, which are also chosen by a certain percentage of students. Faulkner (1977) adds that suitable alternative answers can be very difficult indeed to find. There are several studies investigating whether distractors work and describing how to find working distractors, see Tarrant, Ware and Mohammed (2009) and Ali, Carr and Ruit (2016).
While these two studies investigated medical questions where the answers were terms, in this paper we investigate mathematics questions with numerical answers. Lerchenberger and Donner (2024) study mathematical single choice tasks and state that it seems of utmost importance that task designers should be aware of the fact that the choice of distractors has

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an oversized influence on the average score and is therefore of great importance. Hence, it requires special attention. They define the concept of a trap and subdivide this in various categories and mention that the inclusion of potential traps can be used as a conscious means to create tricky tasks that require self-monitoring of the students in an exam setting.

Feng et al. (2024) explains as the name implies, distractors in single choice questions are typically formulated to align with the common errors students would make or misconceptions students would exhibit. These distractors are chosen because students either i) lack the necessary knowledge of the skills tested in the question to accurately identify the key as the correct answer, or ii) hold misconceptions that result in selecting a specific distractor as the correct answer. While single choice questions offer many advantages for student knowledge evaluation, manually crafting high-quality questions is a demanding and labour-intensive process. Specifically, high-quality distractors should be plausible enough to mislead students and not so evidently incorrect to be identified easily. Furthermore, we investigate to what extent the distractors influence how confident students are about the correctness of their answer, as well as how much time they need to answer the questions. As far as we are aware, the effect on confidence and time has not yet been investigated in any study.

Methodology

In order to investigate the effect of different distractors, we conducted an experiment with the students of a large calculus lecture course for the department D-BAUG (civil and environmental engineers) at the ETH Zurich. All students who were enrolled in this course were allowed to participate. The experiment was conducted as a single choice quiz via Moodle, the teaching and learning platform of ETH Zurich. The quiz consisted of 10 single choice questions on integral calculus, each with 4 possible answers, and related to the previously covered lecture content. For each question, exactly one of the 4 possible answers was correct.
When formulating the questions, particular attention was paid to the following points, which according to the literature should always be taken into account with multiple or single choice questions (cf. Haladyna (2004), Krebs (2019)):

- The questions are linguistically clear and formulated as briefly as possible.
- The questions do not contain any superfluous information.
- No personal names are used.
- There is only one correct answer. The question does not allow for different interpretations.
- All possible answers are visually comparable.

For each of the 10 mathematical questions, the students also had to indicate how confident they were about their answer (very confident - somewhat confident - somewhat uncertain - very uncertain). While all students were asked the same questions in the same order, the three distractors, i.e. the incorrect answer options, were different in each case. The students were randomly divided into two groups, with one set of distractors used for each group. (More details on the choice of distractors in the next paragraph).

After the mathematical questions, we added another question asking about the total time needed, where the students could choose from 5 options (0-15 min, 16-30 min, 31-45 min, 46-60 min, >60 min).

The students solved the quiz without supervision in their free time. As an incentive for participating, the students then received a ‘bonus point’ (independent of their performance), which indirectly led to a grade bonus of around 0.015 on the final exam (on a scale from 1 to 6). Due to the experimental design, it was to be expected that some students would use unauthorised aids or would answer the questions at random with as little time as possible. In order to exclude these students from the analysis, the quiz included an additional question about whether they had answered the questions conscientiously. This was accompanied by a note that the answer to this question had no influence on the bonus points awarded.

The quiz was completed by a total of 170 students out of approximately 280, with 79 in the first group and 91 in the second group. When cleaning the data, those who did not tick ‘yes’ to the question on conscientiousness or who did not agree to their answers being analysed in anonymised form were excluded. As a result, a total of 18 students were excluded. We also excluded four other students who had only scored one or two points and were therefore below the expected value of 2.5 points. As a result, the data of 72 subjects in Group 1 and 76 subjects in Group 2 were analysed.

For the evaluation of the data, we opted for a mixed form: On the one hand, we draw some very obvious and interesting conclusions just by ‘looking’ at the data. On the other hand, we analyse the data with a mixed binary regression model. In particular, this method provides a significant statement about the entire experiment, while direct observations relate more to individual tasks.

Choice of distractors

For Group 1 we followed the literature and tried to design functioning distractors, i.e. distractors that will actually be chosen by a certain percentage of the students. Our guiding principle here was to detect common errors and misconceptions and build distractors from them. The term ‘common’ here, of course, refers only to the errors we predicted (from experience and analysing old exams). While some of these distractors actually turned out to be enormously attractive during the analysis, others were hardly ever chosen.

For Group 2 we constructed three distractors, which are visibly similar to the ones of Group 1, but which are not obtained whilst making the errors used for Group 1. ‘Visibly similar’ here means that there are no distractors that are out of the ordinary, which would be immediately excluded even without being able to solve the task. Care was therefore taken to ensure that the same type of distractors (natural number, rational number, trigonometric expression, expression with π, expression with e, roots) as in Group 1 were also offered as possible answers in Group 2. The order of magnitude of the distractors in Group 2 was also comparable to that in Group 1.

In general, we followed the principle that it should be hard to deduce the right answer by simply looking at all answers and using symmetry arguments (cf. Question 1 below).

In the following section we have picked two questions that demonstrate particularly well how we constructed the distractors for both groups - the total set of questions together with an explanation of the distractors in Group 1 can be found in the appendix.

Examples

Question 1 is a very basic exercise about integration by parts. The correct solution is

$$\int_0^1 2x \cdot \mathrm{e}^x \,\mathrm{d}x = [2x\mathrm{e}^x]_0^1 - \int_0^1 2\mathrm{e}^x \,\mathrm{d}x = 2\mathrm{e} - (2\mathrm{e} - 2) = 2.$$

Question 1

Calculate the following integral: $\int_0^1 2x\mathrm{e}^x \, \mathrm{d}x =$

Answer options Group 1:

- (a) 0
- ✓ (b) 2
- (c) e
- (d) 4e − 2

Answer options Group 2:

- (a) 1
- ✓ (b) 2
- (c) 3e
- (d) 5e + 1

Figure 1: Question 1 from the quiz.

The following common errors were used to design the distractors:

(a) If a student accidentally differentiates in the first summand as well, he would get $[2\mathrm{e}^x]_0^1 - \int_0^1 2\mathrm{e}^x \, \mathrm{d}x = [2\mathrm{e}^x]_0^1 - [2\mathrm{e}^x]_0^1 = 0$. The same distractor can also be obtained with another error, namely by assuming $\mathrm{e}^0 = 0$ at the very end of the correct calculation. Here, we would like to point out that the answer 0 can already be identified as incorrect purely geometrically, since a non-negative function is being integrated. Nevertheless, we decided to offer this distractor as a choice, because students often calculate stubbornly without questioning the result.

(c) If instead of the product both factors are integrated individually, one gets $[x^2\mathrm{e}^x]_0^1 = \mathrm{e}$.

(d) If the minus sign is forgotten in the process of integrating by parts, one gets $[2x\mathrm{e}^x]_0^1 + \int_0^1 2\mathrm{e}^x \, \mathrm{d}x = 2\mathrm{e} + (2\mathrm{e} - 2) = 4\mathrm{e} - 2$.

Care was taken to ensure that the distractors in Group 2 were visibly similar to those in Group 1. Instead of 0 we offered 1 as the first distractor, since they both are very special integers. Instead of e, the answer 3e was offered, as this also contains Euler's number and does not appear more complicated. In accordance with the distractor $4\mathrm{e} - 2$ from Group 1, we built a linear combination of Euler’s number and the number 1, namely $5\mathrm{e} + 1$, as the last distractor. Note that in both cases two answers were integers and two linear combinations with e. Hereby we hoped not to focus too much on one or the other as the symmetry does not give away anything about the nature of the answer (integer or irrational).

Question 8 deals with a triple integral that needs to be solved with the ‘change of variables’ method. The correct answer can be calculated using cylindrical coordinates resulting in

$$\iiint_Z \frac{x^2 + y^2}{z^2} \mathrm{d}V = \int_1^3 \int_0^{2\pi} \int_0^2 \frac{r^2}{z^2} r \, \mathrm{d}r \, \mathrm{d}\varphi \, \mathrm{d}z = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{4} r^4\right]_0^2 = 2\pi \cdot \frac{2}{3} \cdot 4 = \frac{16\pi}{3}.$$

Question 8

Consider the cylinder

$$Z = \{(x, y, z) \in \mathbb{R}^3 \mid 0 \le x^2 + y^2 \le 4\ ,\ 1 \le z \le 3\}$$

Calculate the following integral: $\iiint_Z \frac{x^2 + y^2}{z^2}\, \mathrm{d}V =$

Answer options Group 1:

- (a) $\frac{32\pi}{9}$
- ✓ (b) $\frac{16\pi}{3}$
- (c) $\frac{32\pi}{3}$
- (d) $\frac{256\pi}{3}$

Answer options Group 2:

- (a) $\frac{24\pi}{9}$
- ✓ (b) $\frac{16\pi}{3}$
- (c) $\frac{48\pi}{3}$
- (d) $\frac{140\pi}{3}$

Figure 2: Question 8 from the quiz.

The following distractors, based on common errors, were selected for Group 1:

(a) If the r in the volume element is forgotten, one gets
$\int_1^3 \int_0^{2\pi} \int_0^2 \frac{r^2}{z^2}\, \mathrm{d}r\, \mathrm{d}\varphi\, \mathrm{d}z = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{3}r^3\right]_0^2 = 2\pi \cdot \frac{2}{3} \cdot \frac{8}{3} = \frac{32\pi}{9}.$

(c) If both the r is forgotten in the volume element and r is used for $x^2 + y^2$ and hence, the upper limit of r is taken as 4, one gets
$\int_1^3 \int_0^{2\pi} \int_0^4 \frac{r}{z^2}\, \mathrm{d}r\, \mathrm{d}\varphi\, \mathrm{d}z = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{2}r^2\right]_0^4 = 2\pi \cdot \frac{2}{3} \cdot 8 = \frac{32\pi}{3}.$

(d) If the upper limit of the radius is taken as 4 instead of 2, the resulting calculation is
$\int_1^3 \int_0^{2\pi} \int_0^4 \frac{r^2}{z^2}\, r\, \mathrm{d}r\, \mathrm{d}\varphi\, \mathrm{d}z = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{4}r^4\right]_0^4 = 2\pi \cdot \frac{2}{3} \cdot 64 = \frac{256\pi}{3}.$

Again, we have chosen visibly very similar numbers as distractors for Group 2.

Analysis

First, we examined the extent to which the total number of points achieved (1 point per correctly answered question) of students in Group 1 differed from those in Group 2. Since the students were randomly divided into the two groups, it can be assumed that the total number of points achieved in both groups is normally distributed and has a similar variance. Thus, a Student t-test can be carried out, whereby the null hypothesis is that there is no difference between the two groups in the total scores achieved by the students. The mean received points were 0.4 higher in Group 2 than in Group 1 ($p = 0.019$).

In the next step we dived deeper into the details and analysed how well the groups answered each question. In contrast to the total score, the data set here is binary. By simply screening the data much can be observed when studying the following issues:

- Differences between the two groups with regard to the correctness of the answer
- Frequency with which the respective distractors were chosen
- Students' confidence about the correctness of their answer depending on the group

We will show our findings in an example. Analysing the answer behaviour in Question 8 (Table 1, Table 2), we observe that Group 2 outperforms Group 1. We observe however that in Group 1 not only more often the wrong distractors were chosen, but that this also happens with greater confidence. In Group 2 it seems that wrong answers were mainly picked by guessing.

Group 1	Total	Very confident	Somewhat confident	Somewhat uncertain	Very uncertain
(a)	17	2	7	5	3
(b)	29	13	13	3	0
(c)	13	2	4	2	5
(d)	12	5	4	0	3

Table 1: Answers to Question 8 by Group 1.

Group 2	Total	Very confident	Somewhat confident	Somewhat uncertain	Very uncertain
(a)	9	2	1	2	4
(b)	47	15	14	9	9
(c)	11	0	0	3	8
(d)	6	0	0	2	4

Table 2: Answers to Question 8 by Group 2.

For the deeper statistical analysis, we used a mixed binary regression. Correctness was modelled as the dependent variable, and group membership and certainty, as well as their interaction, were the fixed predictors. In addition, both the corresponding student ID and the question ID were included as random intercepts. The random intercepts take into account the dependency between individual questions and individual students. It is therefore assumed that the correctness of the answer depends on which question it is (difficulty of the question) and which student has answered it (mathematical ability of the student).

We would like to specifically mention the following significant results, which support the observations made in the descriptive evaluation:

1) Ignoring security levels, students from Group 2 perform better overall. (Group 1: 65 % correct answers, Group 2: 81 % correct answers). This difference is statistically significant (OR: 0.43, $p<0.001$).
2) While the very or somewhat uncertain students in both groups perform similarly poorly, there are significant differences between the probabilities for a correct answer between the two groups for the somewhat confident and very confident students, with Group 2 performing significantly better (Table 3, Figure 3).

Certainty	Odds Ratio	SE	Z-Ratio	P-Value
Very Uncertain	0.58	0.20	-1.59	0.112
Somewhat Uncertain	1.13	0.34	0.41	0.683
Somewhat Confident	0.22	0.07	-4.46	<0.0001
Very Confident	0.23	0.09	-3.84	0.0001

Table 3: Posthoc Contrasts between Group 1 and Group 2 for each level of certainty. P-values are uncorrected.

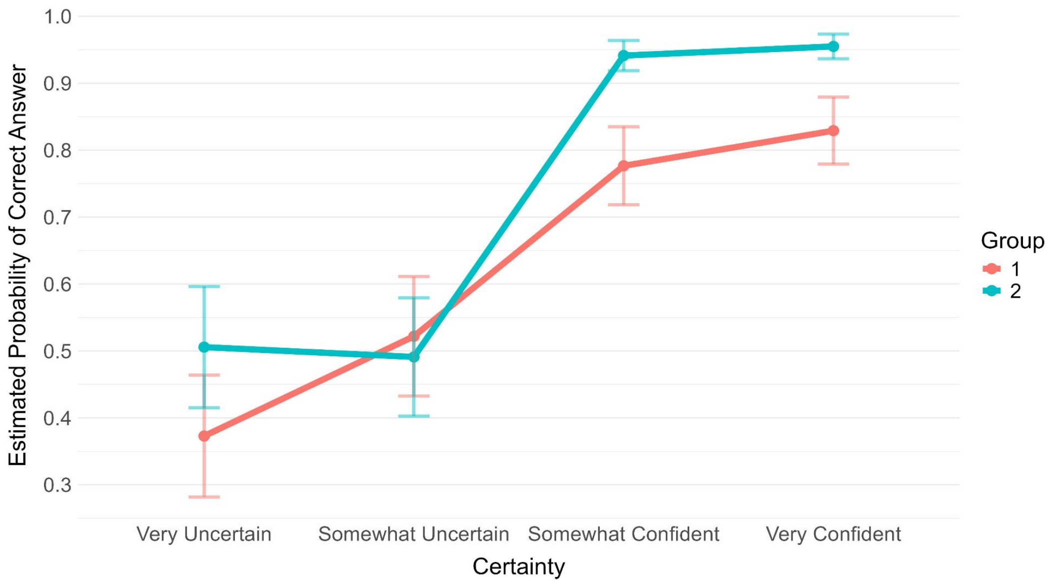

Figure 3: Interaction between Group Membership and Certainty on the Estimated Probability of Correct Responses.

Summary and outlook

As we had expected, the students from Group 2 performed significantly better overall. The obvious explanation is as follows: When students from Group 2 make a common error or have a misconception that we used to create the distractors of Group 1, they get a result that is not available for selection. This means that they have to rethink their answer and thus have the chance to still get the correct solution after all. However, the students from Group 1 which are making the same mistake get a result that corresponds to one of the answer options. Consequently, they mark this incorrect answer and move on to the next question.

It is also explainable that students from Group 1 are excessively often somewhat or even very confident compared to those from Group 2, although they picked a distractor: Since these students arrive at a result from a common error or misconception that is offered for selection, they feel confirmed in their (wrong) answer. They are therefore lulled into a false sense of security by these distractors.

However, one hypothesis that was not confirmed by the experiment is the following: Since the students from Group 2 receive a result that is not available for selection if they calculate incorrectly and therefore have to reconsider their calculation, we expected that they would need more time overall to answer the questions. Yet, it appears that both groups needed roughly the same amount of time to answer the questions. On the one hand, however, this corresponding question only gave us an imprecise time indication, and on the other hand we have no data on the time taken per task. Although we do not see any noticeable differences between the groups in terms of the time required, we cannot rule out the possibility that there are some.

We observed - as was to be expected - that for very hard (only few students could answer correctly) or for very easy (almost all students could answer correctly) questions, the role of the distractors is not so important. However, for medium difficulty questions the distractors play a crucial role in the answering behaviour of the students. It is important to be aware of this when creating multiple or single choice tasks. In our opinion, there is no one right type of distractor. Distractors like those in Group 2 give students the opportunity to realise their mistakes themselves and learn directly from them. This may be very good in practising situations, as they do not give the students a false sense of security and instead gives an opportunity to learn from their own mistakes. For graded tests on the other hand, it may be better to use distractors of the type in Group 1. Special care is required if students receive different versions for an exam. In this case, it is absolutely essential that the distractors in all versions are comparable to each other. In particular, we advise never to have one version with distractors as in Group 1 and another version with distractors as in Group 2. In this case, students' exam success would strongly depend on which version of the exam they receive.

Moreover, when creating distractors like those of Group 1, one needs to be very careful: It is important to have a clear idea about what is tested in the question and what common errors and misconceptions could look like. Common errors that could occur, but are not actually due to the topic at hand in this question, should be avoided e.g. when testing integration by parts the minus in the formula seems crucial. However, by adding for example trigonometric functions, other sign errors could occur resulting perhaps even in the correct answer by doing two things wrong.

As we were surprised that the students in Group 2 did not need more time than the ones in Group 1 and as we cannot exclude that this was because of imprecise measurement, we suggest for future research to do a more careful analysis of the time used when different types of distractors are chosen.

As our study only spanned a short time period, we were not able to say anything about the differences between the two groups in the long-term learning. We think it would be very interesting to study this more carefully and to find out whether e.g. the Group 2 type of distractors led to better and deeper understanding.

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Appendix: Questions from Moodle Quiz with explanation of choice of distractors

Question 1

Calculate the following integral: $\int_0^1 2x\mathrm{e}^x \,\mathrm{d}x =$

Answer options Group 1:	Answer options Group 2:
(a) 0	(a) 1
✓ (b) 2	✓ (b) 2
(c) e	(c) 3e
(d) $4\mathrm{e} - 2$	(d) $5\mathrm{e} + 1$

Correct calculation: $\int_0^1 2x \cdot \mathrm{e}^x \,\mathrm{d}x = [2x\mathrm{e}^x]_0^1 - \int_0^1 2\mathrm{e}^x \,\mathrm{d}x = 2\mathrm{e} - (2\mathrm{e} - 2) = 2$

Choice of distractors for Group 1:

(a) If a student accidentally differentiates in the first summand as well, he would get $[2\mathrm{e}^x]_0^1 - \int_0^1 2\mathrm{e}^x \,\mathrm{d}x = [2\mathrm{e}^x]_0^1 - [2\mathrm{e}^x]_0^1 = 0$. The same distractor can also be obtained with another error, namely by assuming $\mathrm{e}^0 = 0$ at the very end of the correct calculation. Here, we would like to point out that the answer 0 can already be identified as incorrect purely geometrically, since a non-negative function is being integrated. Nevertheless, we decided to offer this distractor as a choice, because students often calculate stubbornly without questioning the result.

(c) If instead of the product both factors are integrated individually, one gets $[x^2\mathrm{e}^x]_0^1 = \mathrm{e}$.

(d) If the minus sign is forgotten in the process of integrating by parts, one gets $[2x\mathrm{e}^x]_0^1 + \int_0^1 2\mathrm{e}^x \,\mathrm{d}x = 2\mathrm{e} + (2\mathrm{e} - 2) = 4\mathrm{e} - 2$.

Question 2

Use the substitution $x = \sin(u)$ to calculate the following integral: $\int_0^1 \sqrt{1-x^2}\,\mathrm{d}x =$

Answer options Group 1:

✓ (a) $\frac{\pi}{4}$
(b) 1
(c) $\sin(1)$
(d) $\frac{1}{2} + \frac{1}{4}\sin(2)$

Answer options Group 2:

✓ (a) $\frac{\pi}{4}$
(b) $\frac{\pi}{3}$
(c) 2
(d) $\frac{1}{4} + \sin(2)$

Correct calculation:
$\int_0^1 \sqrt{1-x^2}\,\mathrm{d}x = \int_0^{\pi/2} \sqrt{1-\sin(u)^2}\cos(u)\,\mathrm{d}u = \int_0^{\pi/2} \cos(u)^2\,\mathrm{d}u = \frac{1}{2}\int_0^{\pi/2}(1+\cos(2u))\,\mathrm{d}u$
$= \frac{1}{2}\left[u + \frac{1}{2}\sin(2u)\right]_0^{\pi/2} = \frac{\pi}{4}$

Choice of distractors for Group 1:

(b) If instead of $\cos(u)\,\mathrm{d}u$ one writes only $\mathrm{d}u$ after the substitution, one gets $\int_0^{\pi/2} \cos(u)\,\mathrm{d}u = [\sin(u)]_0^{\pi/2} = 1$.
(d) If the integral limits are not adjusted when making the substitution, one gets $\int_0^1 \cos(u)^2\,\mathrm{d}u = \frac{1}{2}\left[u + \frac{1}{2}\sin(2u)\right]_0^1 = \frac{1}{2} + \frac{1}{4}\sin(2)$.
(c) If both mistakes are done at the same time, one gets $\int_0^1 \cos(u)\,\mathrm{d}u = [\sin(u)]_0^1 = \sin(1)$.

Question 3

Calculate the following integral: $\int_0^2 \int_0^3 \left(3x^2 + 2y\right)\,\mathrm{d}x\,\mathrm{d}y =$

Answer options Group 1:

(a) 17
(b) 31
(c) 42
✓ (d) 66

Answer options Group 2:

(a) 15
(b) 34
(c) 53
✓ (d) 66

Correct calculation:
$\int_0^2 \int_0^3 (3x^2 + 2y)\,\mathrm{d}x\,\mathrm{d}y = \int_0^2 [x^3 + 2xy]_0^3\,\mathrm{d}y = \int_0^2 (27 + 6y)\,\mathrm{d}y = [27y + 3y^2]_0^2 = 54 + 12 = 66$

Choice of distractors for Group 1:

(b) If the plus gets handled incorrectly and instead two single integrals are calculated, one gets $\int_0^2 2y\,\mathrm{d}y + \int_0^3 3x^2\,\mathrm{d}x = [y^2]_0^2 + [x^3]_0^3 = 4 + 27 = 31$.

(a) If additionally to the already described mistake, also the limits for the integrals are interchanged, one gets $\int_0^2 3x^2 \, \mathrm{d}x + \int_0^3 2y \, \mathrm{d}y = [x^3]_0^2 + [y^2]_0^3 = 8 + 9 = 17$.
(c) If the double integral is calculated with limits for x and y interchanged, one gets $\int_0^3 \int_0^2 (3x^2 + 2y) \, \mathrm{d}x \, \mathrm{d}y = \int_0^3 [x^3 + 2xy]_0^2 \, \mathrm{d}y = \int_0^3 (8 + 4y) \, \mathrm{d}y = [8y + 2y^2]_0^3 = 42$.

Question 4

If $f : \mathbb{R}^2 \to \mathbb{R}$ is a continuous function, then $\int_{-2}^{2} \int_{(x+2)^2}^{8\sqrt{x+2}} f(x,y) \, \mathrm{d}y \, \mathrm{d}x =$

Answer options Group 1:

(a) $\int_{(x+2)^2}^{8\sqrt{x+2}} \int_{-2}^{2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

(b) $\int_{0}^{16} \int_{-2}^{2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

✓ (c) $\int_{0}^{16} \int_{\frac{y^2}{64}-2}^{\sqrt{y}-2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

(d) $\int_{0}^{16} \int_{\sqrt{y}-2}^{\frac{y^2}{64}-2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

Answer options Group 2:

(a) $\int_{(x+2)^2}^{8\sqrt{x+2}} \int_{0}^{4} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

(b) $\int_{0}^{4} \int_{-2}^{2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

✓ (c) $\int_{0}^{16} \int_{\frac{y^2}{64}-2}^{\sqrt{y}-2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

(d) $\int_{0}^{16} \int_{\sqrt{y}}^{y^2-2} f(x,y) \, \mathrm{d}x \, \mathrm{d}y$

Correct calculation: Since $(0 \le)\, y \le 8\sqrt{x+2}$ if and only if $\frac{y^2}{64} - 2 \le x$, and $(x+2)^2 \le y$ if and only if $x \le \sqrt{y} - 2$, the correct answer is (c).

Choice of distractors for Group 1:
(a) This is obtained by interchanging the order of integration without adjusting the limits.
(b) This is obtained by adjusting the limits for the y-Integral only.
(d) This is obtained if the upper and lower limits of x are swapped.

Question 5

Calculate the following integral: $\int_0^3 \int_0^2 \int_{-1}^{0} x^2 y \, \mathrm{d}x \, \mathrm{d}y \, \mathrm{d}z =$

Answer options Group 1:

(a) $\frac{2}{3}$

✓ (b) 2

(c) 6

(d) 18

Answer options Group 2:

(a) $\frac{2}{5}$

✓ (b) 2

(c) 4

(d) 15

Correct calculation:
$\int_0^3 \int_0^2 \int_{-1}^0 x^2 y \, \mathrm{d}x \, \mathrm{d}y \, \mathrm{d}z = \int_0^3 1 \, \mathrm{d}z \cdot \int_0^2 y \, \mathrm{d}y \cdot \int_{-1}^0 x^2 \, \mathrm{d}x = [z]_0^3 \cdot \left[\frac{1}{2}y^2\right]_0^2 \cdot \left[\frac{1}{3}x^3\right]_{-1}^0 = 3 \cdot 2 \cdot \frac{1}{3} = 2.$

Choice of distractors for Group 1:
- (a) This is obtained if the integration by z is completely ignored.
- (c) This is obtained if the integrand is ignored and simply the volume of the cuboid $[0,3] \times [0,2] \times [-1,0]$ is calculated.
- (d) If the limits of integration for x and z are interchanged, one gets $\int_0^3 x^2 \, \mathrm{d}x \cdot \int_0^2 y \, \mathrm{d}y \cdot \int_{-1}^0 1 \, \mathrm{d}z = \left[\frac{1}{3}x^3\right]_0^3 \cdot \left[\frac{1}{2}y^2\right]_0^2 \cdot [z]_{-1}^0 = 9 \cdot 2 \cdot 1 = 18.$

Question 6

The area in the I. quadrant which is bounded by the curve $y = 5 - x^2$ as well as the x- and y-axis, gets rotated around the y-**axis**. What is the volume of the resulting body?

Answer options Group 1:

- ✓ (a) $\frac{25}{2}\pi$
- (b) $\frac{1000}{3}\pi$
- (c) $\frac{10\sqrt{5}}{3}\pi$
- (d) $\frac{40\sqrt{5}}{3}\pi$

Answer options Group 2:

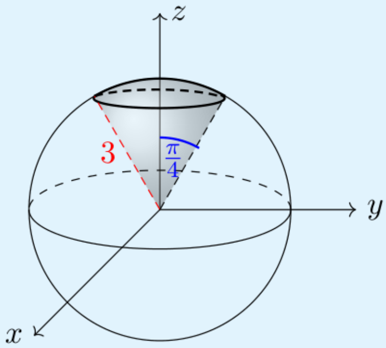
- ✓ (a) $\frac{25}{2}\pi$
- (b) $\frac{800}{3}\pi$
- (c) $\frac{5\sqrt{7}}{3}\pi$
- (d) $\frac{30\sqrt{7}}{3}\pi$

Correct calculation: $V = \pi \cdot \int_0^5 (\sqrt{5-y})^2 \, \mathrm{d}y = \pi \cdot \int_0^5 (5-y) \, \mathrm{d}y = \pi \cdot \left[5y - \frac{1}{2}y^2\right]_0^5 = \frac{25}{2}\pi.$

Choice of distractors for Group 1:
- (b) With rotation around the x-axis and hence, no use of the inverse function, one gets $\pi \cdot \int_0^5 (5-x^2)^2 \, \mathrm{d}x = \pi \cdot \int_0^5 (25 - 10x^2 + x^4) \, \mathrm{d}x = \pi \cdot \left[25x - \frac{10}{3}x^3 + \frac{1}{5}x^5\right]_0^5 = \frac{1000}{3}\pi.$
- (d) The same mistake as before with the upper limit taken as $\sqrt{5}$ gives $\pi \cdot \int_0^{\sqrt{5}} (5-x^2)^2 \, \mathrm{d}x = \pi \cdot \int_0^{\sqrt{5}} (25 - 10x^2 + x^4) \, \mathrm{d}x = \pi \cdot \left[25x - \frac{10}{3}x^3 + \frac{1}{5}x^5\right]_0^{\sqrt{5}} = \frac{40\sqrt{5}}{3}\pi.$
- (c) If the mistake is to forget to square the integrand, one gets $\pi \cdot \int_0^5 \sqrt{5-y} \, \mathrm{d}y = \pi \cdot \left[-\frac{2}{3}(5-y)^{3/2}\right]_0^5 = \frac{10\sqrt{5}}{3}\pi.$

Question 7

Calculate the volume of the following spherical cut-out:



Answer options Group 1:

(a) $V = 9\pi$
(b) $V = 9\sqrt{2}\pi$
(c) $V = 9\left(1 - \frac{1}{\sqrt{2}}\right)\pi$
✓ (d) $V = 9\left(2 - \sqrt{2}\right)\pi$

Answer options Group 2:

(a) $V = 8\pi$
(b) $V = 3\sqrt{2}\pi$
(c) $V = 6\left(1 + \sqrt{2}\right)\pi$
✓ (d) $V = 9\left(2 - \sqrt{2}\right)\pi$

Correct calculation:

$V = \int_0^{2\pi}\int_0^{\pi/4}\int_0^3 1 \cdot r^2\sin(\vartheta)\,\mathrm{d}r\,\mathrm{d}\vartheta\,\mathrm{d}\varphi = 2\pi \cdot \int_0^3 r^2\,dr \cdot \int_0^{\pi/4}\sin(\vartheta)\,\mathrm{d}\vartheta$
$= 2\pi \cdot \left[\frac{1}{3}r^3\right]_0^3 \cdot [-\cos(\vartheta)]_0^{\pi/4} = 2\pi \cdot 9 \cdot \left(-\frac{\sqrt{2}}{2} + 1\right) = 9(2 - \sqrt{2})\pi.$

Choice of distractors for Group 1:

(a) Since with angle π, one would get the volume of the whole sphere, a possible mistake is to think that with angle $\pi/4$ one gets a fourth of it, i.e. $\frac{1}{4} \cdot \frac{4\pi \cdot 3^3}{3} = 9\pi$.
(b) Taking the wrong volume element $r^2\cos(\vartheta)\,\mathrm{d}r\,\mathrm{d}\vartheta\,\mathrm{d}\varphi$, one gets
$\int_0^{2\pi}\int_0^{\pi/4}\int_0^3 1 \cdot r^2\cos(\vartheta)\,\mathrm{d}r\,\mathrm{d}\vartheta\,\mathrm{d}\varphi = 2\pi \cdot \int_0^3 r^2\,\mathrm{d}r \cdot \int_0^{\pi/4}\cos(\vartheta)\,\mathrm{d}\vartheta = 2\pi \cdot \left[\frac{1}{3}r^3\right]_0^3 \cdot [\sin(\vartheta)]_0^{\pi/4}$
$= 2\pi \cdot 9 \cdot \frac{\sqrt{2}}{2} = 9\sqrt{2}\pi.$
(c) Taking the wrong volume element $r\sin(\vartheta)\,\mathrm{d}r\,\mathrm{d}\vartheta\,\mathrm{d}\varphi$, one gets
$\int_0^{2\pi}\int_0^{\pi/4}\int_0^3 1 \cdot r\sin(\vartheta)\,\mathrm{d}r\,\mathrm{d}\vartheta\,\mathrm{d}\varphi = 2\pi \cdot \int_0^3 r\,\mathrm{d}r \cdot \int_0^{\pi/4}\sin(\vartheta)\,\mathrm{d}\vartheta = 2\pi \cdot \left[\frac{1}{2}r^2\right]_0^3 \cdot [-\cos(\vartheta)]_0^{\pi/4}$
$= 2\pi \cdot \frac{9}{2} \cdot \left(-\frac{\sqrt{2}}{2} + 1\right) = 9\left(1 - \frac{1}{\sqrt{2}}\right)\pi.$

Other potential mistakes in this exercise could have been to completely forget the volume element or to take the wrong volume element r as for polar coordinates. However, these mistakes would leave to results with π^2, which looks somewhat different and hence, we didn't provide them as distractors.

Question 8

Consider the cylinder

$$Z = \{(x, y, z) \in \mathbb{R}^3 \mid 0 \leq x^2 + y^2 \leq 4\ ,\ 1 \leq z \leq 3\}$$

Calculate the following integral: $\iiint_Z \frac{x^2 + y^2}{z^2}\,\mathrm{d}V =$

Answer options Group 1:

- (a) $\frac{32\pi}{9}$
- ✓ (b) $\frac{16\pi}{3}$
- (c) $\frac{32\pi}{3}$
- (d) $\frac{256\pi}{3}$

Answer options Group 2:

- (a) $\frac{24\pi}{9}$
- ✓ (b) $\frac{16\pi}{3}$
- (c) $\frac{48\pi}{3}$
- (d) $\frac{140\pi}{3}$

Correct calculation: Using cylindrical coordinates, one gets

$\iiint_Z \frac{x^2+y^2}{z^2}\,\mathrm{d}V = \int_1^3 \int_0^{2\pi} \int_0^2 \frac{r^2}{z^2} r\,\mathrm{d}r\,\mathrm{d}\varphi\,\mathrm{d}z = \int_0^{2\pi} 1\,\mathrm{d}\varphi \cdot \int_1^3 \frac{1}{z^2}\,\mathrm{d}z \cdot \int_0^2 r^3\,\mathrm{d}r = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{4}r^4\right]_0^2$
$= 2\pi \cdot \frac{2}{3} \cdot 4 = \frac{16\pi}{3}$.

Choice of distractors for Group 1:

(a) If r is forgotten in the volume element, one gets
$\int_1^3 \int_0^{2\pi} \int_0^2 \frac{r^2}{z^2}\,\mathrm{d}r\,\mathrm{d}\varphi\,\mathrm{d}z = \int_0^{2\pi} 1\,\mathrm{d}\varphi \cdot \int_1^3 \frac{1}{z^2}\,\mathrm{d}z \cdot \int_0^2 r^2\,\mathrm{d}r = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{3}r^3\right]_0^2 = 2\pi \cdot \frac{2}{3} \cdot \frac{8}{3} = \frac{32\pi}{9}$.

(d) If the upper limit of the radius is wrongly taken as 4 instead of 2, one gets
$\int_1^3 \int_0^{2\pi} \int_0^4 \frac{r^2}{z^2} r\,\mathrm{d}r\,\mathrm{d}\varphi\,\mathrm{d}z = \int_0^{2\pi} 1\,\mathrm{d}\varphi \cdot \int_1^3 \frac{1}{z^2}\,\mathrm{d}z \cdot \int_0^4 r^3\,\mathrm{d}r = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{4}r^4\right]_0^4 = 2\pi \cdot \frac{2}{3} \cdot 64$
$= \frac{256\pi}{3}$.

(c) If at the same time the r is forgotten in the volume element and $x^2 + y^2$ is wrongly taken as r, one gets
$\int_1^3 \int_0^{2\pi} \int_0^4 \frac{r}{z^2}\,\mathrm{d}r\,\mathrm{d}\varphi\,\mathrm{d}z = \int_0^{2\pi} 1\,\mathrm{d}\varphi \cdot \int_1^3 \frac{1}{z^2}\,\mathrm{d}z \cdot \int_0^4 r\,\mathrm{d}r = 2\pi \cdot \left[-\frac{1}{z}\right]_1^3 \cdot \left[\frac{1}{2}r^2\right]_0^4 = 2\pi \cdot \frac{2}{3} \cdot 8 = \frac{32\pi}{3}$.

Question 9

We consider the circular ring

$$R = \{(x,y) \in \mathbb{R}^2 \mid 1 \leq x^2 + y^2 \leq 3\}$$

Calculate the following integral: $\iint_R \frac{y^2}{x^2+y^2}\, \mathrm{d}A =$

Answer options Group 1:

✓ (a) π
(b) $\frac{3\pi}{2}$
(c) 4π
(d) $\left(\sqrt{3}-1\right)\pi$

Answer options Group 2:

✓ (a) π
(b) $\frac{5\pi}{2}$
(c) 3π
(d) $\left(2-\sqrt{3}\right)\pi$

Correct calculation: Using polar coordinates one gets

$$\iint_R \frac{y^2}{x^2+y^2}\, \mathrm{d}A = \int_0^{2\pi}\int_1^{\sqrt{3}} \frac{r^2\sin^2(\varphi)}{r^2} r\, \mathrm{d}r\, \mathrm{d}\varphi = \int_0^{2\pi} \sin^2(\varphi)\, \mathrm{d}\varphi \cdot \int_1^{\sqrt{3}} r\, \mathrm{d}r$$
$$= \int_0^{2\pi} \frac{1}{2}(1-\cos(2\varphi))\mathrm{d}\varphi \cdot \int_1^{\sqrt{3}} r\, \mathrm{d}r = \left[\frac{1}{2}\left(\varphi - \frac{1}{2}\sin(2\varphi)\right)\right]_0^{2\pi} \cdot \left[\frac{1}{2}r^2\right]_1^{\sqrt{3}} = \pi \cdot 1 = \pi.$$

Choice of distractors for Group 1:

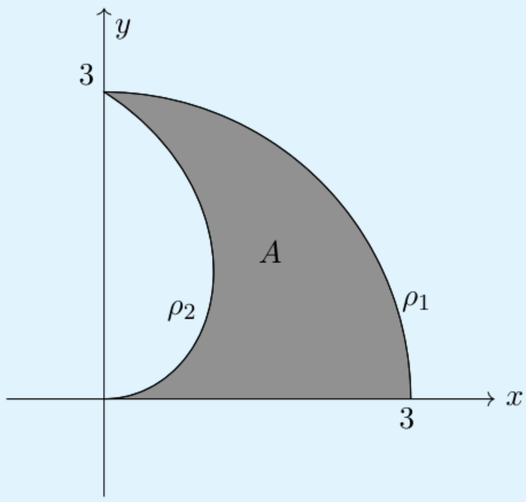
(b) If the lower limit of the radius is mistakenly taken as 0, one gets
$$\int_0^{2\pi}\int_0^{\sqrt{3}} \frac{r^2\sin^2(\varphi)}{r^2} r\, \mathrm{d}r\, \mathrm{d}\varphi = \int_0^{2\pi} \sin^2(\varphi)\, \mathrm{d}\varphi \cdot \int_0^{\sqrt{3}} r\, \mathrm{d}r = \left[\frac{1}{2}\left(\varphi - \frac{1}{2}\sin(2\varphi)\right)\right]_0^{2\pi} \cdot \left[\frac{1}{2}r^2\right]_0^{\sqrt{3}}$$
$$= \pi \cdot \frac{3}{2} = \frac{3\pi}{2}.$$

(c) If the upper limit of the radius is mistakenly taken as 3 instead of $\sqrt{3}$, one gets
$$\int_0^{2\pi}\int_1^{3} \frac{r^2\sin^2(\varphi)}{r^2} r\, \mathrm{d}r\, \mathrm{d}\varphi = \int_0^{2\pi} \sin^2(\varphi)\, \mathrm{d}\varphi \cdot \int_1^{3} r\, \mathrm{d}r = \left[\frac{1}{2}\left(\varphi - \frac{1}{2}\sin(2\varphi)\right)\right]_0^{2\pi} \cdot \left[\frac{1}{2}r^2\right]_1^{3}$$
$$= \pi \cdot \left(\frac{9}{2} - \frac{1}{2}\right) = 4\pi.$$

(d) If the factor r is forgotten in the area element, one gets
$$\int_0^{2\pi}\int_1^{\sqrt{3}} \frac{r^2\sin^2(\varphi)}{r^2}\, \mathrm{d}r\, \mathrm{d}\varphi = \int_0^{2\pi} \sin^2(\varphi)\, \mathrm{d}\varphi \cdot \int_1^{\sqrt{3}} 1\, \mathrm{d}r = \pi \cdot \left(\sqrt{3}-1\right) = \left(\sqrt{3}-1\right)\pi.$$

Question 10

Calculate the area in the first quadrant which gets enclosed by the curves with polar coordinate representation $\rho_1(\varphi) = 3$ and $\rho_2(\varphi) = \frac{6\varphi}{\pi}$.



Answer options Group 1:

- (a) $A = \frac{9\pi}{8}$
- ✓ (b) $A = \frac{3\pi}{2}$
- (c) $A = \frac{9\pi}{4}$
- (d) $A = \frac{57\pi}{4}$

Answer options Group 2:

- (a) $A = \frac{5\pi}{4}$
- ✓ (b) $A = \frac{3\pi}{2}$
- (c) $A = \frac{17\pi}{8}$
- (d) $A = \frac{45\pi}{4}$

Correct calculation:

$$A = \frac{1}{2}\int_0^{\pi/2} \rho_1(\varphi)^2 \, \mathrm{d}\varphi - \frac{1}{2}\int_0^{\pi/2} \rho_2(\varphi)^2 \, \mathrm{d}\varphi = \frac{1}{2}\int_0^{\pi/2} 3^2 \, \mathrm{d}\varphi - \frac{1}{2}\int_0^{\pi/2} \left(\frac{6\varphi}{\pi}\right)^2 \mathrm{d}\varphi = \frac{9\pi}{4} - \frac{18}{\pi^2}\left[\frac{1}{3}\varphi^3\right]_0^{\pi/2}$$
$$= \frac{9\pi}{4} - \frac{18}{\pi^2} \cdot \frac{\pi^3}{24} = \frac{3\pi}{2}.$$

Choice of distractors for Group 1:

(d) If instead of subtracting the two integrals, one does the subtraction in the integrand before taking the square, one gets
$\frac{1}{2}\int_0^{\pi/2} (\rho_1(\varphi) - \rho_2(\varphi))^2 \, \mathrm{d}\varphi = \frac{1}{2}\int_0^{\pi/2} \left(9 - \frac{6\varphi}{\pi}\right)^2 \mathrm{d}\varphi = \frac{1}{2}\int_0^{\pi/2} \left(81 - \frac{108\varphi}{\pi} + \frac{36\varphi^2}{\pi^2}\right) \mathrm{d}\varphi = \frac{57\pi}{4}.$

(a) The attempt to calculate the area with elementary geometry and subtracting from the area of a quarter disc with radius 3 by mistake the area of a half disc of radius 1.5, one gets $\frac{1}{4} \cdot \pi \cdot 3^2 - \frac{1}{2} \cdot \pi \cdot 1.5^2 = \frac{9}{8}\pi$.

(c) If the area of the quarter disc is calculated without subtracting anything, one gets $\frac{9\pi}{4}$.

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