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ABSTRACT

Problem- and project-based learning (PBL) is often highlighted as a valuable approach for addressing the need for interdisciplinarity in engineering education. However, studies indicate that applied projects in engineering education tend to be limited to a single discipline. This article presents a new project typology which can be applied in engineering education. The typology is based on an action research study in a systemic PBL environment. The model presented has two dimensions: a) the complexity of teams, ranging from single team to networks of teams, and b) the complexity of interdisciplinarity, ranging from disciplinary projects to broad interdisciplinary projects. This results in the identification of six different project types. This typology can be used as a conceptual framework for interdisciplinary learning throughout engineering education. The project types embrace both single-team projects and larger projects consisting of multiple teams working together on complex problems.

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PBL; interdisciplinarity; variation in projects; project types; system projects; engineering education

Introduction

The last 30 years have seen increasing societal expectations for engineers to develop new technologies to address climate change and other issues encompassed by the Sustainable Development Goals (SDGs) (UNESCO, 2017). Societal problems have increased in complexity, as have the technologies developed in response to these problems. Engineering education is thus facing the challenge of preparing engineering graduates to participate in the development of complex systems within a context of broader engineering collaboration. Civil engineering, which has always employed a systems approach in construction processes, has in the last ten years taken on an even broader system scope, e.g. integrating digital technologies to control operations in houses and integrating sustainability and life cycle assessments in the choice of materials. Climate issues require a broader technical approach; for example, road and bridge construction must address increasing flooding risks, creating new challenges for mechanical and energy engineers in the innovation and implementation process, which is itself a highly collaborative process (Messerli et al., 2019). Systems thinking is part of innovation and impacts all elements in the innovation or production process (UNESCO, 2021).

Often, the scope of complex problems also requires interaction with social science or humanities disciplines, which results in an even broader collaboration. For example, when a complex technical system, such as a satellite, is being sent into orbit, issues concerning national legislation governing data and confidentiality arise. An essential part of the development of smart cities is understanding

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the habits of their citizens, which can influence issues such as waste handling and the need to create an understandable sorting mechanism for users. And while working to improve clean water supply in Africa does involve designing and building water pumps, we have known for many years that this narrow approach by itself does not solve the problem and that it is indeed necessary to understand the local community, the cultural context, the technical infrastructure, and the implementation processes (Müller, 1990).

Academia's response to the SDGs and the increasing complexity of engineering work is the use of an interdisciplinary approach to analyse and solve problems. This has become policy in the EU as mission-driven programmes increasingly involve interdisciplinary collaboration. Collaborations bringing STEM (Science, Technology, Engineering and Mathematics) into SSH (Social Science and Humanities) and SSH into STEM are points on the European agenda for the development of engineering education (Keraudren, 2018; Sonetti, Arrobbio, Lombardi, Lami, & Monaci, 2020). Developing solutions to achieve the SDGs requires a more comprehensive understanding of all relevant disciplines, both within the technical domain and across STEM and SSH (Grasso & Burkins, 2010; Kolmos, 2021). No single discipline will be able to achieve the SDGs alone, and it will be necessary in the future to be able to cross boundaries between disciplines, professions, organisations, cultures, and individuals. Organisations – both public and private – struggle with communication between divisions. Cultures – national, ethnic, and organisational – differ in their practices, experiences, and languages. For engineers to develop technology in a sustainable way, they need to understand technology from a broader societal perspective (Müller, 2011).

Problem- and project-based learning (PBL) is often highlighted as one of the routes that engineering education should take to meet this requirement for greater interdisciplinarity (Hadgraft & Kolmos, 2020; Van den Beemt et al., 2020). Research on interdisciplinary projects in engineering education reveals that students struggle to work in interdisciplinary project teams and to create common mental models for collaboration (MacLeod & van der Veen, 2020; Richter & Paretti, 2009; Routhe et al., 2021).

Interdisciplinary knowledge construction is among the theoretical roots of PBL, and the original intention of PBL was for it to be applied to authentic and real-life problems (Illeris, 2010). However, literature reviews indicate that this is not always the case when PBL methods are applied in engineering schools, as they are mostly implemented at the course level in a way which maintains the existence of tight disciplinary boundaries (Chen, Kolmos, & Du, 2021; Helle, Tynjälä, & Olkinuora, 2006).

Over the last 30 years, categorisations of different project types have been developed. Based on the relationship between discipline and problem, three project types have been defined: the assignment-based project, the subject project, and the problem project (De Graaf & Kolmos, 2003; Kolmos, 1996). In the assignment-based project, the problem, subject and methods are chosen beforehand. In the subject project, either the problem or the subject is chosen beforehand, with the other open for the student to freely choose. The problem project uses a problem as the starting point, meaning that the problem will determine the choice of discipline and method. The latter is often an interdisciplinary project. Another related framework for understanding PBL projects is presented by Helle et al. (2006), in which there are three project types: a project where students should apply knowledge and techniques; the project component with a broader scope and here understood as relation to real world and being more interdisciplinary; and finally the project orientation which is the basic driver in the curriculum with a high degree of student freedom and with instructions as support to the students' learning.

These two categorisations project types were developed during the 1990s and the 2000s, and although both categorisations do embrace interdisciplinary projects, neither provides an updated framework for interdisciplinary projects to address complex problems as the categorisations are based on single teams. Complex societal problems require students to learn complex collaboration structures and there is a need to distinguish between various types of interdisciplinary knowledge constructions and teams.

In a review by Chettiparamb (2007), the OECD discussed interdisciplinarity in teaching and its general aims and functions as early as in 1972. However, most of the twentieth century has been framed by disciplinarity despite acknowledgements of the interactions between disciplinarity and interdisciplinarity (Klein, 2006). Chettiparamb (2007) referred in her review to various approaches for interdisciplinary teaching, and it was also noted that although interdisciplinarity was considered appealing in an educational context, the idea into pedagogy and teaching requires much more than an understanding of the concept. Studies conclude that more research is needed on curriculum and instruction patterns in interdisciplinary programmes (Lattuca & Knight, 2010). More recently, Beddoes (2020) furthermore points to an underdeveloped understanding of how student team projects can be designed taking into consideration that engineers increasingly need to work in interdisciplinary settings.

More general concepts and approaches that include the learning dimension need to be applied to the development of engineering education (Everett, 2016). Models of project types based on engineering education practice can be seen as a way to nurture this transformation process. Therefore, this article aims to create a nuanced understanding of interdisciplinary project types which can be applied in engineering education.

Narrow and broad interdisciplinarity

The first step in understanding the interdisciplinary collaborative aspect is to understand the nature of interdisciplinarity, of which the literature mentions three variations: Multi-, Inter-, and Transdisciplinarity (Borrego & Newswander, 2010; Keestra & Menken, 2016; Klein, 2010).

These three concepts are illustrated in Figure 1, based on Keestra and Menken (2016). The multidisciplinary approach ensures that the problems are looked at from multiple disciplinary angles and that different disciplinary solutions are considered. There is an exchange of information and knowledge, but there is no real integration in the solutions which are eventually proposed. The interdisciplinary approach, on the other hand, is an integrated approach, leading to a shared solution. The transdisciplinary approach is defined slightly differently across the diverse literature on the subject (Bernstein, 2015; Mullally, Byrne, & Sage, 2017a; Nicolescu, 2006), but generally adds another dimension closely related to interdisciplinarity, with both the shaping of new knowledge fields and the crossing of the boundaries between academia and practice (Gibbons et al., 1994), which might also foster new perspectives on how disciplinary and interdisciplinary knowledge is applied. Although it is possible to distinguish multi-, inter-, and transdisciplinarity in theory, however, in practice the concepts are used in many different ways. It is important to emphasise

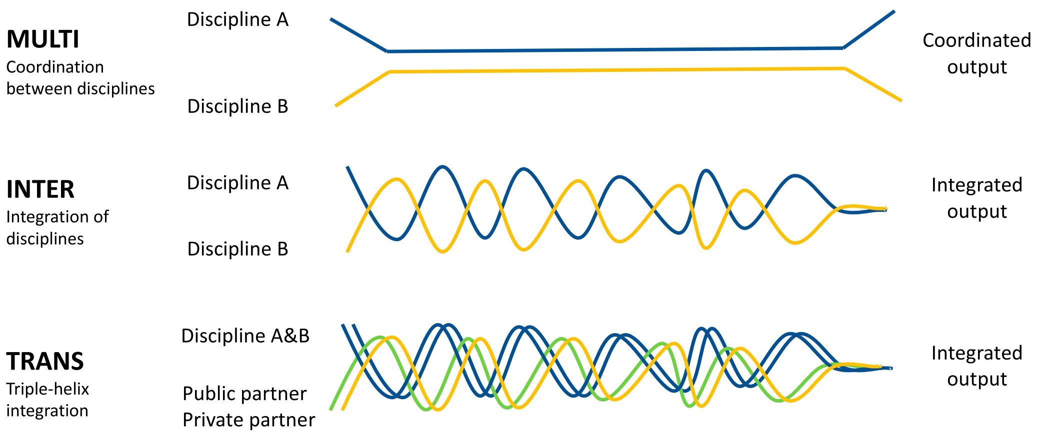

Figure 1. Multi-, inter-, and transdisciplinarity based on Keestra and Menken (2016).

that there are three very different collaboration patterns. At the one end of the spectrum is a multidisciplinary system in which collaboration can happen in parallel systems; at the other end of the scale is inter- and transdisciplinary collaboration, which involves close collaboration on a common development of products or solutions. There is no doubt that the latter is more challenging.

There are other conceptualisations of interdisciplinary approaches. For example, Klein (2006) drew a distinction between narrow and broad interdisciplinary approaches, whereby a narrow approach is characterised by shared knowledge paradigms, while a broad one is characterised by different knowledge paradigms: for example, engineering versus humanities. Obviously, it is easier to collaborate with and understand others from nearby disciplines which share knowledge paradigms as compared to the crossing of boundaries from, for example, civil engineering to psychology. Lattuca and Knight conducted a study on the understanding of interdisciplinarity and likewise found huge variations in conceptual understandings and noted the use of other synonyms like 'cross-disciplinary' and 'interdepartmental', as well as variations in practices (Lattuca & Knight, 2010). Disciplines exist as social constructions of diverse knowledge domains, and departments exist as an organisational frame for collaboration (Roy, 2021; Roy & Roy, 2021). Practices are contextual and vary from situation to situation, and the combination of knowledge paradigms will depend on concrete practices.

Another approach to defining interdisciplinarity is to focus on the fact that the reality of implementing large-scale engineering projects always consists of communities, boundaries, and brokers, regardless of the specific lens through which it is viewed (Wenger, 2001). In this conceptualisation, community represents practices, boundaries represent the diversity between communities, and brokers represent the learners trying to overcome the boundaries. Whenever we work in the boundary zones as brokers, issues arise which pose challenges to collaboration and professional identity (Boden, Borrego, & Newswander, 2011).

Richter and Paretti's work on the concept of disciplinary egocentrism notes two very important barriers in interdisciplinary collaboration: first, students do not learn the cognitive relationships between their own discipline and other interdisciplinary subjects; second, there is a lack of acknowledgement between the multiple technical and nontechnical domains of a given interdisciplinary problem (Richter & Paretti, 2009). Disciplinary humility can be seen as a prerequisite for transcendent knowledge generation (Mullally, Sage, & Byrne, 2017b). Based on this understanding, Tripp and Shortlidge argue that the lack of acknowledgement can also be seen from the opposite perspective as the need for learning disciplinary humility, which is one of the founding principles for creating interdisciplinary understanding (Tripp & Shortlidge, 2019). They identify five elements for creating interdisciplinary understanding: disciplinary grounding, different research methods, advancement through integration, and collaboration across disciplines, which can only be learned efficiently if the basic attitude is humility and curiosity towards the world outside the disciplinary boundaries (Tripp & Shortlidge, 2019). At the end of the day, the success of interdisciplinary collaboration relies on the culture of the profession and epistemological self-reflection of the boundaries to other disciplines.

Interdisciplinary collaboration

To work in an interdisciplinary manner, teams that bring together multiple disciplines are needed. Engineering has long been perceived to require team working competencies as engineering is characterised by a systems approach (Atkinson, 2001; Schaller & Hadgraft, 2013; Trevelyan, 2014). Much of the literature in engineering education addresses cooperative learning, collaborative learning and team effectiveness; however, it more often does so in a disciplinary setting than in an interdisciplinary context.

There has been development in the conceptual understanding from more cooperative learning to collaborative learning and teamwork. Cooperative learning is defined as the instructional use of small groups in the classroom with the goal of supporting students to improve their own and each other's learning (Johnson, Johnson, & Smith, 2014). The use of small groups is based on a variety of learning methodologies, including organising learning so that students are linked through positive interdependence, assessing each individual student, and facilitating the development of social skills (Johnson, Johnson, & Smith, 1998). Collaborative learning is seen as a participatory and student-driven learning process deconstructing the power relations in the traditional classroom (Bruffee, 1995; Dillenbourg, 1999; Illeris, 2010). It is an umbrella concept that covers a range of teaching and learning approaches in education as well as in work, and which is based both on an understanding of learning as an active, social, and constructive process and on educational approaches to facilitate the collaborative learning process (Smith & MacGregor, 1992). Multiple types of collaborative learning approaches exist, including active learning, a broad category of learning methodologies; problem-based learning, which emphasises cases and study groups; and project-based learning, in which students work on common goals and products (Savin-Baden, 2014). Bruffee (1995) compared the advantages and disadvantages of collaborative and cooperative learning and concluded that the non-hierarchical structure of collaborative learning reflects a lack of educational accountability and might be a disadvantage (Bruffee, 1995). The disadvantage of cooperative learning, on the other hand, is that it seems to continue the hierarchical learning structures in its instructional approach. In practice, this might not be the case, as there is huge variation in the way collaborative learning is applied in the classroom as well as in the curriculum.

Teamwork, meanwhile, is defined as a process in which individuals collaborate in a group with the aim of achieving a common goal. There are different types of teams defined by the level of integration of the collaboration, ranging from groups with individual goals to more integrated collaboration with the goal of becoming a high-performing team (Katzenbach & Smith, 2006). Whereas collaborative learning does not necessarily involve the development of a shared product, the team concept is based on an understanding of shared goals that impact the collaborative process. In interdisciplinary teams, the collaborative aspects are crucial as team members will have diverse disciplinary or professional backgrounds, cognitive understandings and cultural expectations.

Borrego and Cutler conclude that curriculum alignment, teamwork and interdisciplinary communication are crucial to improving the interdisciplinarity of the engineering curriculum (Borrego & Cutler, 2010). Team success is a concept applied in the literature which highlights phases and components for effective teamwork. Other studies identify five key components to consider for effective teamwork: social loafing, interdependence, conflicts, trust, and shared mental models (Borrego, Karlin, McNair, & Beddoes, 2013). The key to successful teamwork is for the team members to have shared mental models; in order to achieve this, it is necessary to develop interdependence and trust, together with the ability to solve conflicts and minimise social loafing (Borrego et al., 2013). Shared mental models are a core condition for successful teams as there needs to be a shared understanding of the knowledge applied in the collaborative process. This does not mean that all members must share the same level of disciplinary knowledge, but rather that they should have enough knowledge of each of the fields represented in the team to be able to co-construct knowledge for a common goal. Beddoes proposed new aspects of shared mental models by applying a framework called Interdisciplinary Teamwork Artefacts and Practices (ITAP), which offers a new perspective on the collaboration that takes place within a team (Beddoes, 2020).

In most of the literature on interdisciplinary teams, the issues raised can also be used as a characteristic of disciplinary teams. Repko, Szostak, and Buchberger (2019) underlined the cognitive dimension of collaboration in particular as being troublesome; however, they emphasised that there is a series of traits that are needed for interdisciplinary collaboration, such as an entrepreneurial mindset (taking risks), a love of learning (being excited to learn something new), self-reflection (awareness of one's own strengths and weaknesses), intellectual courage (acceptance of and respect for other viewpoints), and patience and empathy (active listening). All these traits are extensions of collaborative competencies in projects, but they involve deep reflections and project skills as an extended component of the generic PBL competencies (Kolmos, Bertel, Holgaard, & Routhe, 2020). At one moment, team members must listen, and at the next, they must exercise the courage to move and take risks. In any situation, as a learner who is challenged by new knowledge, new disciplines, language, learning culture, or organisation, these skills will be important for the individual learner in order to learn how to cross boundaries, and it is important to prepare students to participate in these boundary crossings and interdisciplinary collaborations in their professional lives. This learning affects both academic staff and students in developing their professional identities (McNair, Newswander, Boden, & Borrego, 2011).

From single teams to teams in networks

Engineering is in many ways characterised by a systems approach. Technologies consist of multiple subsystems and components derived from different academic disciplines, and engineering practice is a sum of interactions across learned disciplinary boundaries. In the development of more comprehensive systems, there is normally a series of work packages that have to be coordinated and organised.

If engineering education is to prepare students for these working patterns, students need to learn to collaborate both within teams and across teams – that is, to work through boundary-spanning approaches (Schotter, Mudambi, Doz, & Gaur, 2017). Network learning is a form of organisational learning associated with networks of teams or organisations that interact with a common purpose (Knight, 2002). Network learning can occur in more solid network structures or in loosely coupled structures, described in Engeström's theory as teams and knots; in this framework, the team-structured approach is seen as an outdated way of organising work (Engeström, 2008). Network learning is one of the theories underpinning Computer-Supported Collaborative Learning (CSCL) and is seen as a critical and inquiring approach to support connections, collaboration, and new learning designs (McConnell, Hodgson, & Dirckinck-Holmfeld, 2012). It is aimed at both informal and formal learning environments and embraces digital learning in all forms, with an open approach to the concept of learning and the learning environment. Engeström has pointed out that the hierarchical nature of teams and the use of teams as a way to structure human collaboration are changing. The book *From Teams to Knots* highlights that static teams are being replaced by much more flexible approaches to collaboration, such as a fluid and distributed approach to the organisation of work and embedded collaboration. Teams must be understood in their contexts and in light of the specific objectives that lie at the centre of the collaboration (Engeström, 2008). This understanding aligns with the concept of communities of practice with boundary objects and brokers. For interdisciplinary teams, one of the boundary objects can be the problem itself, and the brokers are the individuals who collaborate across communities of practice (Wenger, 2001).

No matter which language is applied, there is a clear need for engineers to learn to collaborate in diverse team structures. Students need to learn to be flexible and able to participate in any collaborative pattern. Sometimes they need to work in small teams, and sometimes they are part of huge networks. Sometimes they work on systems designs, and sometimes they have to contribute to the development of specific devices. Learning to work in all of these diverse roles involves a new understanding of groups and teams as being dependent on the specific objectives or activity, which will determine the type of collaboration needed.

Research question

The above scoping review of interdisciplinarity highlights the challenges facing implementation of truly interdisciplinary project-based learning. The aim of the article is to contribute to addressing those challenges by creating a variated understanding of interdisciplinary project types which can be applied in engineering education.

As detailed above, interdisciplinarity and collaboration can be characterised by variations on two scales. The interdisciplinarity scale ranges from multidisciplinary to narrow and broad interdisciplinary and transdisciplinary. The collaborative scale ranges from cooperation to collaboration and networks. Combining the two scales establishes a framework for defining types of interdisciplinary projects and study how these are aligned with students' experiences.

Thereby, we have worked from the following research question: (1) *What characterises students' experiences in interdisciplinary projects? (2) What are the challenges and opportunities of broad and narrow interdisciplinary projects?* In the understanding of interdisciplinarity we follow Klein (2006), including the distinction between narrow and broad interdisciplinarity.

Methodology

Aalborg University (AAU) serves as the context of this study. Not only does this university have a well-known educational model for engineering education (Graham, 2018), but the university has also experimented with different types of interdisciplinary projects, including faculties' initiatives, input from researchers and research on student experiences. This context of study is thus highly appropriate for a methodology linking theory and practice.

Context of study

AAU engineering students work in project teams for half of their study time, and normally submit one project per semester. These projects are mostly confined to specific disciplines, but in the problem analysis phase, the project teams bring in other disciplines to analyse and solve the problems. The size of project teams at AAU ranges from six to eight students in the first year to smaller teams of two to four in the later semesters (Kolmos, Fink, & Krogh, 2004). Throughout the curriculum, the types of problems students work on varies from more open problems to narrower disciplinary problems, which are very often based on the needs of companies. Students formulate their own problems in their projects and direct their own learning within the overall framework of the curriculum (Kolmos et al., 2020).

In 2019, a more structured approach to develop interdisciplinary projects across various faculties was introduced (Routhe et al., 2021). The scoping of the interdisciplinary projects has addressed both narrow and broad interdisciplinary learning designs. We have been involved in researching these projects and have, through active dialogue, co-constructed a model of feasible project types in engineering education. Due to the PBL philosophy at AAU, the conceptualisation of learning is linked to an experimental and pragmatic approach to learning, taking inspiration from Kolb (1984). The methodology is also linked to a pragmatic approach aimed at research for practice (Creswell, 2014).

Action research

The narrow and broad interdisciplinary projects at AAU have been studied using an action research approach to link faculty initiatives, input from researchers on practice, and research on experiences from working in interdisciplinary projects.

Action research involves a research process of collecting data and collaborating with involved participants for further direction and design. Action research is aimed at developing and changing practice and ultimately informing theory (Somekh, 2005; Willis & Edwards, 2014). In contrast to design-based research (DBR), it does not take its point of departure in theory, is not necessarily planned by researchers, and does not distinguish between the researcher/designer and professionals implementing change in the field (Reimann, 2011). While DBR takes its point of departure in research and contributes to research, action research is a broader and more inclusive concept in which researchers normally begin by engaging with practitioners on their terms. The initiatives can be shaped by both the researchers and the practitioners.

Action research involves an iterative process between practice and research. In the development of new project types, this iterative process involves developing a model, understanding it, and using that understanding to further develop it. Figure 2 illustrates the main research process. Alongside this process, the researchers have had weekly conversations and exchanges of ideas on how to proceed or what could be done, both as more formal meetings and as corridor talks. This has been a very close collaboration based on a shared interest in developing successful new models. However, decisions on the development of the project designs have been made by the educational managers and the involved academic staff. They have listened to input from the authors and from the students.

The overall development process has consisted of two iterations of project models based on empirical data. The iterations have followed a timeline set by faculty initiatives. The first iteration was focused on the development of the concept of Megaprojects. The AAU pro-rector established an initiative to implement broad interdisciplinary projects addressing the Sustainable Development Goals. The coordination of this project was headed by the Technical Faculty of IT and Design. The development of this model was prompted by the development of two project types. One of these was a bottom-up inter-team disciplinary initiative in the Department of Computer Science, the so-called Giraf project (Graham, 2022a, 2022b); the other was an interdisciplinary Megaproject, which was carried out as part of an institutional initiative to increase students' opportunities for interdisciplinary work and was intended to resemble the potential larger projects that students will face in their future profession. The Megaprojects were designed for inter-team and interdisciplinary learning. During the first iteration, the authors followed and commented on the initiatives, while the research activities centred on the Megaprojects.

The 'Interdisciplinary PBL methodologies in engineering education and work' (InterPBL) research project, funded by the Poul Due Jensen Foundation, further increased opportunities for follow-up research on these new incentives at AAU. The second iteration was based on initiatives supplementing and responding to experiences from the Megaprojects, as well as two upcoming project types. One of these, leadENG, was a narrow interdisciplinary project type undertaken across teams; the other, Hackathon, was a one-team project involving students from disciplines across faculties. The

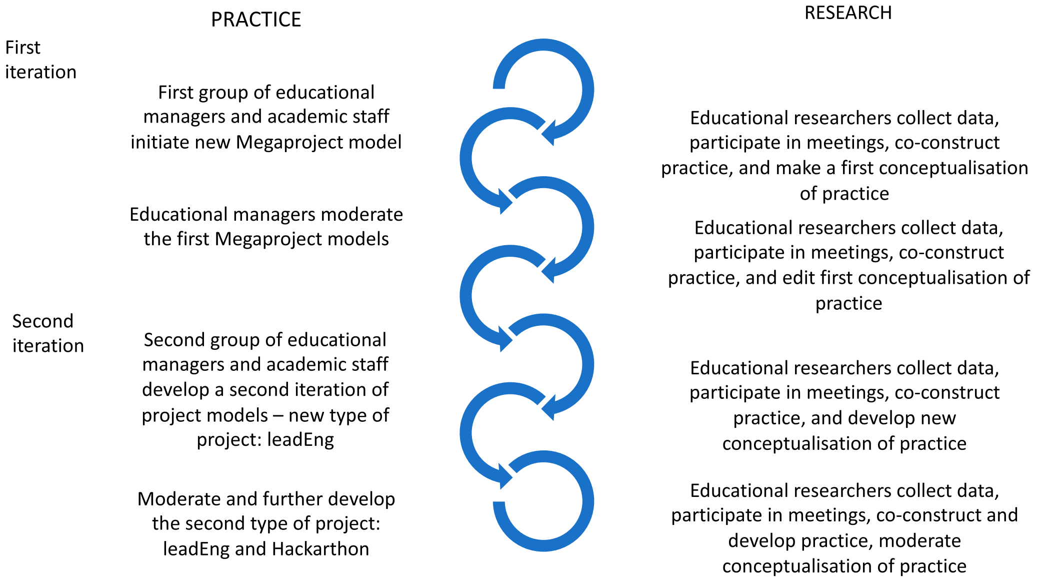

Figure 2. Action research methods applied in this project.

institutional case addressed has a high proportion of transdisciplinary aspects related to the different project types, e.g. in terms of company projects (Holgaard & Kolmos, 2018).

Data-collection

Table 1 provides an overview of the data collected, organised chronologically and under different projects. We elaborate on the data-collection processes below.

For both iterations a qualitative approach to data has been used. All interviews have been conducted using a semi-structured approach, giving the interviewer the possibility to elaborate and follow up on questions as the interview progress. Each interview was collected as a focus group interview with one semester group participating per interview giving each group the opportunity and time to elaborate on their experiences. The interviews had a duration of approximately an hour each and two researchers have participated in each interview to make sure that one could take notes and keep track on the predetermined interview questions. Even though the interviews have been conducted over several years and from different empirical sources, the interview guides have been fairly identical, see Table 2. A few additional contextual questions have been asked specifically for leadENG and the Megaprojects to clarify processes and experiences specific for that time in the students' education. To minimise language barriers, all interviews have been carried out in Danish. Important to note is that interviews in 2020 and 2021 were conducted online through the platform MS Teams due to Covid 19.

The **first iteration** started with the AAU Megaprojects launched in September 2019. The aim was to enable students to work across faculties and disciplines (STEM/SSH) on complex interdisciplinary problems within a sustainability theme. Based on empirical findings on experiences participating in a broad interdisciplinary project constellation at AAU, Megaprojects had its first iteration in spring 2020. Researchers gave feedback on how the format, collaboration and assessment had been experienced by the students. During the spring of 2020, researchers were invited to follow the process of the project, providing the organisers with ongoing feedback on how to improve and develop the concept from both research and practical points of view. Through observations at both meetings, seminars and the final conference researchers were able to follow activities and development during the semester. After the second round of the AAU Megaprojects, the authors conducted an additional 18 interviews with students, 5 interviews with supervisors and 3 interviews with facilitators elaborating on their views on participation, outcomes, and relevance, providing organisers with a more nuanced picture of the concept. Researchers continued to follow the Megaprojects in autumn 2020 to conduct additional research on interdisciplinary collaboration and project management. Observations from specific events were collected in this period as well.

The **second iteration** started in spring 2021 where the Faculty of Engineering and Science at AAU launched the leadENG concept, introducing narrow interdisciplinary projects for engineering students at the university. LeadENG originates from a desire to enhance students' interdisciplinary competencies by introducing them to other disciplinary understandings closely related to their own. LeadENG built on previous experiences from AAU Megaprojects, though with a much narrower focus. Researchers revised and gave feedback on the concept during summer 2021, at which time it was agreed that students needed a more direct introduction to how they could put their PBL competencies to use. Students worked together in narrow interdisciplinary teams focusing on themes such as 'Small Electrical Vehicles', 'Vertical Windmills' and 'Sterling Engines'. Researchers presented findings on this initiative during the start-up seminar in spring 2022.

In addition to the two interdisciplinary concepts running in 2021, researchers from InterPBL organised a three-day Hackathon in collaboration with a large Danish company to investigate the importance of structure and guidance in supporting the student's collaborative and project management skills. Students worked on authentic problems presented by the company. Further, the Hackathon invited individuals from all faculties at the university to work together in interdisciplinary teams, creating a different team constellation than the clusters of teams in the Megaprojects and leadENG.

Table 1. Overview of data collected from spring 2020-spring 2022.

Year	Project	Data collected	Number of students	Semester	Interdisciplinary constellation	Data processing methods
Iteration 1						
2019	AAU Megaprojects	Semi-structured focus group interviews	3 students	3. Semester 5. Semester 7. Semester	Broad interdisciplinary clusters of teams	Exploratory, data-driven coding on interviews highlighting experiences and issues of concern
		Observations	27 students			Observation sheets focused on processes and interaction
Feedback to organisers on format, alignment and assessment based on experiences from students						
2020	AAU Megaprojects	Semi-structured focus group interviews	18 students 5 supervisors 3 facilitators	4. Semester 6. Semester 8. Semester 10. Semester	Broad interdisciplinary clusters of teams	Exploratory, data-driven coding on interviews highlighting experiences and issues of concern
		Observations	25 students			Observation sheets focused on processes and interaction
Feedback to organisers on format, problem types, collaboration issues, project management and transformation of knowledge from both students, supervisors and facilitators. *(periodic informal follow-up meetings with organisers during the semester)*						
2020	AAU Megaprojects	Observations	20 students	5. Semester 7. Semester	Broad interdisciplinary clusters of teams	Observation sheets focused on processes and interaction
Feedback on format, collaboration and issues of concern based on observations. *(periodic informal follow-up meetings with organisers during the semester)*						
Iteration 2						
2021	leadENG	Semi-structured focus group interviews	15 students	2. Semester	Narrow interdisciplinary clusters of teams	Exploratory, data-driven coding on interviews highlighting experiences and issues of concern
		Observations	35 students			Observation sheets focused on processes and interaction
2021	Hackathon	Observations and feedback from students	8 students	6. Semester 7. Semester 8. Semester 9. Semester 10. Semester	Broad interdisciplinary teams of individuals	Observation protocol (focused on processes, collaboration and project management among the members in the group)
Feedback to organisers on format, alignment and difficulties based on experiences from students. Introduction slides on PBL competencies in interdisciplinary settings for students in spring 2022.						
2022	leadENG	Semi-structured focus group interviews	27 students	2. Semester 6. Semester	Narrow interdisciplinary clusters of teams	Exploratory, data-driven coding on interviews highlighting experiences and issues of concern
		Observations	55 students			Observation sheets focused on processes and interaction

Table 2. Interview guide used in both iteration 1 and 2 across the different cases.

Preliminary questions
Try and tell us about your participation in the ______ project? What did you work with?
Why did you choose to participate in the ______ project?
What did you expect of the process before you started?
Experiences being part of an interdisciplinary project setting
How were your experiences participating in the _______ project? (What functioned well/what did not?)
How was the project structured? (What functioned well/what did not?)
How did you experience the interdisciplinary collaboration among the teams? (Degree of collaboration)
How did you manage the collaboration among the teams? (How many meetings/timing)
What type of knowledge have you shared among the teams? (Difficulties in understanding each other)
Can you try and tell us how (and if) the process has been different from your ordinary semester projects?
Retrospective reflections of their participation
What have you learned being part of ______?
Have you gained a better understanding of your own disciplinary contributions?
What do you think should be done to improve _______ further?

The Hackathon, arranged by the authors together with company employees, took place at the company partner's headquarters over three days as an extracurricular activity, involving students from four different faculties.

The last data was collected in spring 2022, and reflects how improvements and initiatives were experienced, giving researchers an insight into how the different types of interdisciplinary projects were positioned compared to one another. The data have been reported and published and will form the basis for the development from the first iteration to the second iteration of the project models (Bertel, Winther, Routhe, & Kolmos, 2021b; Routhe, Winther, Nguyen, Holgaard, & Kolmos, 2022; Winther, Routhe, Holgaard, & Kolmos, 2022).

Data analysis

All interviews were transcribed through Nvivo and data analysed using a data-driven approach limiting predetermined preunderstandings and prejudice. Through thematic analysis, the coding process enables the researchers to highlight distinct patterns in the data sets and develop categories. These categories were compiled into themes providing researchers with the opportunity to gather and compare interviews across project teams bringing together a coherent narrative for understanding how interdisciplinary project work have been perceived by the interviewees.

For the AAU Megaprojects the overarching themes were structural procedures and the lack of interdisciplinary collaboration. Students were mostly concerned with the lack of structures to support their interdisciplinary teamwork and progress. When coding the data from leadENG, other themes appeared such as focus much more on their inability or failure to put certain competencies into action to improve collaboration and project management among the interdisciplinary teams. The same results were seen at the Hackathon, where students found it difficult to reflect and activate appropriate PBL competencies to support the interdisciplinary processes.

Most of the observations were carried out using an observation protocol, ensuring traceability and transparency in what was observed. The use of a predetermined observation protocol ensured focus on certain areas of interest. The remaining observations have been used as background information for understanding the context of the study. Observations were interesting for this project as they gave researchers insight into how the processes of the interdisciplinary projects were performed. They also gave a nuanced picture of the collaboration in the clusters of teams. Observation protocols were coded focusing on different themes relevant for understanding and developing the interdisciplinary projects. The data from the observation sheets were mostly used as background information to guide the understanding of the structures and processes of the projects and clarify the questions to ask in the interviews.

Data has been processed and results have been shared with the practitioners. We have been aware that the results and interactions have influenced the data. Table 3 gives an overview of the types of interactions provided along the process for the different projects.

Methodological limitations

This research has taken an action research approach which imposed certain methodological limitations. All three interdisciplinary projects have undergone development to ensure their continuation and improvement. The authors were invited to follow and help develop each of the project concepts from when it was launched, and continuous feedback was provided for the organisers based on both empirical data and research. Because of this, certain meetings and talks have been informal, which means that detailed information concerning interactions and co-construction processes cannot be traced. However, such informal meetings have served as important inputs for researchers' interactions.

Researchers have followed both Megaprojects and leadENG through multiple iterations, tracking improvements and changes, whereas Hackathon has only been hosted once to date, though with an aim of rehosting it again in 2023/2024. Another limitation is the number of students participating in the different initiatives. Megaprojects, leadENG and Hackathon are all electives, which results in limited participation and therefore also a limited pool of data.

Furthermore, the positioning of the authors has been slightly different in the 3 cases. In particular, the Hackathon was conducted by the authors and employees at the company, who both taught and facilitated the process. To counteract this, the observations were done by a colleague who was invited to participate to get a second opinion on the data. This colleague has only participated in the collection of data and not in the final analyses.

Findings

In this section, we present the findings from the two iterations based on students' experiences with the three projects: Megaprojects, leadENG and Hackathons.

First iteration of new project types

Initially, project types were conceptualised in a rather coarse-grained fashion representing the differences across disciplinary dimensions. The theoretical framework is based on a differentiation between less or more interdisciplinarity on one axis, and on the other, a continuum from single teams to several teams in a network (Bertel et al., 2021a; Kolmos et al., 2020).

Table 3. Interactions with practice.

Project	Type of interaction with practice
Iteration 1	
Megaprojects	Feedback on how to improve the structure and progression of the concept in making it more clear for both students, facilitators and supervisors. Written feedback on guidelines and deliverables with suggestions for improving the guidelines. Oral feedback through informal meetings for how to secure more reflection and assessment in regard to the competences gained through the students' participation.
Iteration 2	
leadENG	Oral feedback through informal meetings with supervisors on how to improve weekly meetings and seminars with students. Slideshow with main results from interviews with previous participants to support students' collaboration and project management.
Hackathon	Structural and conceptual changes with organisers from the participating company on how to improve the concept in regard to degree of structure, improvement of collaboration between company and students, involvement of company etc.

This resulted in four project types, of which two are within a single discipline and two are interdisciplinary; see Figure 3. The two disciplinary project types are not within the scope of this article. They are, however, the most prevalent in the curriculum. Multi-projects are typically software projects in which several student teams work on a shared problem, such as an app to assist autistic children (Graham, 2022a).

The two types of interdisciplinary projects are, at this stage in the development of the model, called the Interdisciplinary project and the Megaproject. The interdisciplinary project serves the purpose of framing and contextualising the problem and has been practised at AAU since the institution's founding. It is characterised by borrowing knowledge and methods from other disciplines, for example, by applying sociological methods in a user-driven innovation approach or an economic perspective on calculating the economic feasibility. Engineering students do not collaborate with students in other disciplines, but they do apply knowledge from other disciplines and might gain an understanding of different knowledge paradigms.

The first more structured approach to integrate interdisciplinarity in projects was the launch of the Megaproject in 2019, and in this case the interdisciplinarity went beyond borrowing knowledge and methods to encompass interdisciplinary collaboration. With an ambition to get participants from different faculties to collaborate (i.e. broad interdisciplinarity) there were still room for more narrow interdisciplinary collaboration across engineering and science faculties.

The Megaprojects address the SDGs on a large scale, and together with the integration of the SDGs into the engineering curriculum, it was decided that these bigger interdisciplinary projects should be implemented across at least three faculties (Routhe et al., 2021). The Megaprojects consist of project teams from different disciplines at three different faculties. The students must fulfil the specific requirements of their courses of study but collaborate on sustainability problems across the programme. One example of a project topic is waste handling in private households; in this project, student teams from, e.g. environmental management, psychology, and biology work on the various problems they identify through their disciplinary lenses and how these can be solved. The disciplinary teams interact and review each other's work during the process and develop a more comprehensive plan at the end of the project period.

Results from the evaluation of the initial implementation of Megaprojects reveal significant challenges in frameworks that let students continue to focus on their disciplinary learning outcomes and

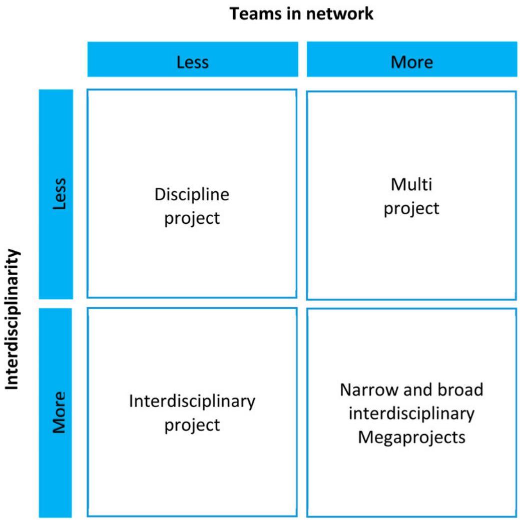

Figure 3. First model of project types (Kolmos et al., 2020).

only add interdisciplinarity as extracurricular activities without formal assessment (Bertel et al, 2021a; Bertel et al., 2021b; Routhe et al., 2021):

1) There were no formal requirements or learning outcomes in the curriculum for the interdisciplinary collaboration in the Megaprojects, except for the disciplinary learning outcomes in the disciplinary study regulations. The interdisciplinary learning outcomes were formulated as extracurricular activities and as a result, the students were more focused on the disciplinary learning outcomes.
2) The semesters were organised differently within the various programmes involved, making it hard to identify a start-up period with common problem understanding across the programmes, i.e. a common phase for problem demarcation and problem solution.
3) The students had difficulties managing the processes partly due to operational differences between programmes and faculties, but also because it was hard to transform their PBL competencies from discipline projects to Megaprojects.
4) The epistemological aspects of the different scientific approaches were a barrier to creating a common understanding within the given time frame. Student teams from the humanities wanted to understand the problem thoroughly, whereas the STEM student teams wanted to begin working on solutions after a much shorter problem analysis period.
5) The management of the Megaprojects was left to the students, and there was a lack of academic staff support on how to relate to other teams and construct interdisciplinary understanding. The students had difficulties in transforming their competencies in disciplinary project work into competencies for interdisciplinary collaboration.

The overall conclusion was that network and interdisciplinary collaboration require teamwork competencies, but that the scaffolding of both student learning and academic support should be reconsidered, and that scaffolding of the curriculum, the students' PBL competencies, and the academic staff's role is a crucial element in the success of interdisciplinary projects (Bertel et al, 2021b).

Similar evaluation results can be found in a study of Twente University's trial implementation of a project across a narrower interdisciplinary approach encompassing applied mathematics, civil engineering and industrial and engineering management (MacLeod & van der Veen, 2020). MacLeod and van der Veen found difficulties in the curriculum structure of the Twente programme, the academic staff's understanding of the collaborative processes, the type of problems, and the relevance of the problems to the various disciplinary learning outcomes. Another study indicated that there are three main barriers to establishing an interdisciplinary project-based curriculum: (1) the organisation of the curriculum, (2) students' competencies in collaborative and interdisciplinary work, and (3) the academic staff's competencies in facilitating interdisciplinary learning (Stentoft, 2017).

In our ongoing interaction with the educational coordinators of the Megaprojects, the researchers observed that the challenges of implementing the Megaproject concepts sparked new discussions. The inputs from the researchers were discussed, but overall, it was difficult to settle on a concept which would offer opportunities for students with different intended learning outcomes to co-construct a solution to a common problem. The discussions among researchers and educational coordinators also showed confusion regarding the concepts used to characterise the different project types, and regarding the conceptual framework in itself (Figure 3). For example: Is borrowing from other disciplines without active collaboration sufficient to be considered interdisciplinary? When did a Multi-project become a Mega project; and what does it mean to be 'Mega'? When is it too narrow – and why is collaboration between different programmes within a department not considered interdisciplinary? At the same time, other initiatives grew, partly as a response to the challenges faced in the Megaprojects. These initiatives offered new student experiences as well as inputs to develop the theoretical framework.

Second iteration – an expanded model for project types in interdisciplinary networks

While the Megaprojects were running, the Faculty of Engineering and Science at AAU introduced new types of projects within a narrower interdisciplinary perspective. Student teams from various engineering disciplines worked on developing technological systems, a much more concrete task for engineering students than starting out by agreeing on problem analysis from various angles across social science and engineering. The engineering disciplines share values, interests, motivation for learning, knowledge paradigms and scientific methodologies, and it might therefore be much easier to create shared mental models in collaboration between engineering disciplines than in collaboration across engineering and social science. The latter can encounter significant differences in areas ranging from values to knowledge paradigms and methodologies, making it more challenging to create shared mental models.

Results from the first leadENG projects in 2021 indicated that the introduction of a narrower problem type helped students find common ground and shared points of departure for their collaborations, managing not only their processes but also their interdisciplinary collaboration better. Students still experienced challenges managing the projects, and scaffolding from facilitators remained necessary to support students' interdisciplinary work; however, these findings indicate that a narrow interdisciplinary project can serve as an important bridge for students to enter broader interdisciplinary projects (Winther et al., 2022). Table 4 presents some of the students' descriptions of their experiences with the leadENG project.

As these comments illustrate, the students were quite positive about the learning experience they had across the engineering programmes. They learned about their own disciplines and about nearby disciplines, and they felt the experience was meaningful for them. It was noted that through a common boundary object, students managed to work more closely together in leadENG, identifying interdependencies and developing an understanding of different disciplines better than students working in broader interdisciplinary Megaprojects (Winther et al., 2022).

In the spring of 2022, based on previous experiences from leadENG in 2021, the students participating in leadENG were introduced to specific PBL processes they would need to be aware of in the coming interdisciplinary setting. By highlighting the experiences from the previous year and

Table 4. *Examples of students' experiences from* leadENG *2021.*

Motivation	*'It has been motivating to know that more teams have been part of this project together, and it has also made the group work more interesting … '(2nd semester student in leadENG2021).*
Different mental models	*'Definitely, that with project management and collaboration across disciplines, it's definitely something to think about. They do not know exactly the same as you. They know something you do not know, and you know something they do not know. There you just have to be a little more aware of how. Maybe you should have a start-up meeting where you just agree on what things and how to calculate them, and what competencies they have, and what they really want here. Before you just get started, there will also be a collaboration over time'. (2nd semester student in leadENG2021).*
Synergy	*'It is about how much we can gain from a project by using each other in this way. You can do so much more. You can quickly get an overview of the system … We have used one another and gained a lot of knowledge from each other'. (2nd semester student in leadENG2021).*
Linked to real life practice	*'The interdisciplinary way of working has been great. Experiencing talking to other teams, who do not do the same as you, gives you a picture of what happens in the real world, which I find extremely cool'. (2nd semester student in leadENG2021).*
Peer learning	*'When we have different competencies across the two lines [disciplines], I think it becomes clear that we really have something to contribute and that we can teach others something. And when we pass on knowledge to others, we understand the elements better ourselves as well'. (2nd semester student in leadENG2021).*
Boundary objects	*'It is a bit different, we will never be able to make the whole car without the other teams. At least not the whole car. We could have resigned a battery and an engine to a fictional car, where it would probably have employed it just some standard. By some random also it had been the car then, also focused on our electric part of cars. But it would be just as realistic or just as good as what we do now. We also get to make a car out of it, as a prototype, which we would not have been able to do ourselves in relation to a lot of different things there, which would have been unrealistic here in the first semester'. (2nd semester student in leadENG2021).*

the importance of the PBL competencies gained in their first semester, students were encouraged to build on these disciplinary competencies when moving into an interdisciplinary project setting. As a result of this approach, students were observed to gain a solid understanding of both narrow and broad interdisciplinarity and the ability to reflect on their own disciplinary positions in relation to others (Routhe, Holgaard, & Kolmos, 2023). Some examples of the students' comments are shown in Table 5.

These quotes illustrate various views of what it would be like working with people outside engineering. No doubt that they appreciate the outcomes from other engineering programmes, and for some of them this has given motivation also to work in broader interdisciplinary contexts, for others they will still find it difficult. Students also found it important to interact with the technology, as was the case in the previous year. Coordination was recognised as very important in interdisciplinary projects and, compared to the previous year, it was noted that the students were better at managing and structuring their interdisciplinary projects, bringing together key persons in each student group in student-established steering groups (Routhe et al., 2023).

Based on these findings from Megaprojects and leadENG, a Hackathon was developed with a large Danish company, creating a space for students to collaborate in broad interdisciplinary teams on societal problems in a limited period of time (three days). To promote and accelerate the interdisciplinary teamwork and management, students were introduced to an entrepreneurial structure for problem-solving and innovation, providing them with guidelines for how to collaborate towards a common goal is shown in Table 6.

Although the students found the event both exciting and meaningful, several students still found it difficult to transform their disciplinary knowledge and experience to the broad interdisciplinary situation without more scaffolding. It is important to note that these students had no previous experience with interdisciplinary group work (Routhe et al., 2022).

A new project typology

The narrow interdisciplinary approach might present fewer challenges for collaboration but may not provide sufficient sustainable solutions to the societal problems we are facing. Engineering cannot solve global sustainability challenges on its own, and the social and economic aspects of solutions to

Table 5. *Examples of increased focus on broad interdisciplinarity in* leadENG *2022.*

Motivation	*'I think it could get really, really interesting at some point if you were to work with fields of study that were not engineering. Then I think it could be fun. And see how it was supposed to go. We certainly have different views on many things'.* (2nd semester student in leadENG2022).
Narrow versus broad interdisciplinarity	*'But now, for example, Energy and Machinery and Production, we kind of resemble each other anyway. It will be something completely different if I suddenly have to go out and communicate something, if I now have some sales managers. And my sales manager does not understand mechanics at all. So, I just have to give some terms that the person understands. And it is clearly a challenge'. (6th semester student in leadENG2022). 'I think there may also be something in the fact that we are all studying to be engineers, so I think there has been a big difference, if you had also had some humanists, then it could have gone completely awry. Just that we all sit with an engineering language in one or another way'. (2nd semester student in leadENG2022).*
Increased competencies	*'So, one thing that works well about it is that you get an insight into what others are doing, so you gain, what can one say, knowledge and perhaps competencies in addition to your own specific field of expertise when you sit and discuss it with other teams and things like that. It just gives a little more'* (2nd semester student in leadENG2022).

Table 6. *Examples of students' experiences from Hackathons.*

Common ground and reflectivity	*'It showed me how I work in interdisciplinary teams, where none actually knows each other beforehand. I also learned the importance of questioning my choices and not agreeing to everything that is brought up in the discussion'.* (Student in Hackathon 2021).
Discipline versus profession	*'I experienced a new environment, where I found a new professional part of me. I have learned a lot about myself, and working together with people I don't know'.* (Student in Hackathon 2021).

these challenges are indispensable. However, if students cannot transform their learning experience directly from disciplinary settings to broad interdisciplinary problem-solving processes, there is a need for improvements in the curriculum. It might be easier for students to transform their learning experience from disciplinary settings to narrow interdisciplinary problem-solving processes as they share the scientific paradigms. In line with this, we propose a model below showing the ideal types of projects (Figure 4), with a clearer distinction between narrow and broad interdisciplinary projects as well as a characterisation of the complexity of the technological system, or subsystem, being addressed.

For each project type, the relationship between the problem and broad interdisciplinarity across STEM and SSH can be either tightly or loosely coupled (Lengwiler, 2006). This constitutes a new dimension in the approach to interdisciplinary collaboration. Lengwiler (2006) identifies four types of interdisciplinary collaboration, defined in two dimensions: cognitive coupling and degree of organisation. This results in four types of interdisciplinary research collaboration: the charismatic and methodological types are tightly coupled, whereas the pragmatic and heuristic types are loosely coupled. The organisational dimension in our case will be determined by the curriculum structures, but the cognitive coupling can be an important factor in determining learning outcomes, and thus significant for educational design. Tightly coupled projects exhibit cognitively integrated relationships that will impact the learning process, whereas loosely coupled ones acknowledge that there is a relationship, but it might have lower priority and the project may therefore employ a much more pragmatic approach. In an ideal world, all projects would be tightly coupled; however, in an educational setting, the level of connection might have to vary as there are still disciplinary learning outcomes to be addressed.

In the **disciplinary project**, the problem is directly connected to a STEM discipline. The starting point for the STEM team's problem-solving process is the need to solve a given narrow technical problem. The solution is based on the use of STEM theories and methods related to the given programme. Although students borrow from other disciplines to analyse the problem from a societal

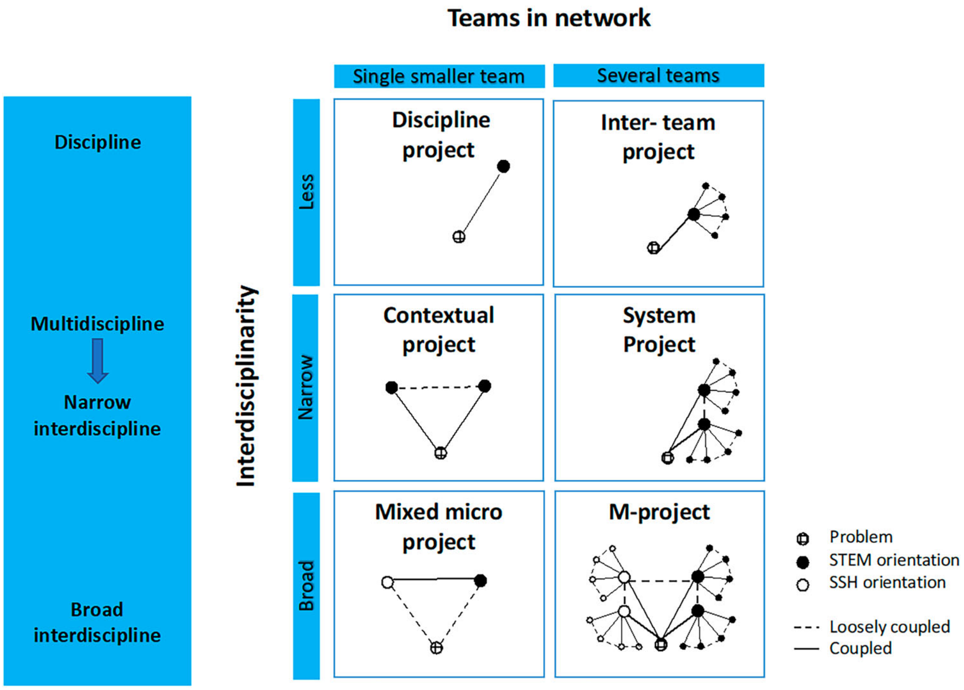

Figure 4. Elaborated model of project types based on Kolmos et al. (2020).

perspective, they still narrow down the process to one of pure technological problem-solving. In this case, the engineering team is loosely coupled to the SSH field of study by adapting theoretical framings and methods from SSH disciplines to target a technological solution to a specific real-life problem. They thus remain within their disciplinary borders in terms of collaboration.

The **inter-team project** remains constrained within the same discipline, but a 'knot' approach sees multiple teams address the same technological system from different angles within the discipline. Each team thereby contributes to the problem-solving process, and complementary contributions are synthesised to solve the overall problem. In this way, the inter-team project holds the potential for solving more complicated problems than the disciplinary project. Examples of inter-team projects are to be found in a newly published report on engineering education (Graham, 2022a, 2022b). The term 'inter-team' replaces the term 'multi-project', as the latter, used without conceptual context, was sometimes misinterpreted as being multi-disciplinary.

Domain projects bring together students from different but closely related educational programmes. These students work within the same epistemological field, drawing on the same sphere of knowledge. In engineering education, this means that the team brings together students from different engineering sub-disciplines, e.g. energy planning and environmental planning working together across planning programmes. In the engineering programme, this can take the form of an elective or a compulsory project related to general engineering, e.g. an engineering design project. As such, the participants from the different programmes are loosely coupled but have very similar STEM orientations and a common problem. This type of project might be a stand-alone mini project integrated into the curriculum or a more extended part of the programme, e.g. a common curriculum at the first year across disciplines. The domain project concept recognises the multidisciplinary, or even narrow interdisciplinary, nature of initiatives put forward in dialogues with staff.

The **System project** is a new concept inspired by the leadENG initiative. The focus remains on the engineering perspective, with a narrow disciplinary view, e.g. involving collaboration among electronics, material science, production and civil engineering. In contrast to the inter-team project, however, at least two programmes from different engineering fields collaborate to illustrate the dependencies of engineering disciplines in technological systems. Another difference from the above-mentioned project types is that the students enter the system project network with different learning objectives, which may make the cognitive coupling between the teams looser. The system project serves a narrow interdisciplinary purpose.

The **mixed micro project** is a single-team project with students representing a broad range of disciplines across engineering and SSH, e.g. organised as a Hackathon. This type of project can differ in size and length and may be of transdisciplinary character involving collaboration with external partners. As the overall purpose of the project is to facilitate competencies for collaborative learning across STEM and SSH boundaries and for student projects, the success of the actual problem-solving process can be more loosely coupled as it is considered less important. The learning objectives are across the disciplines to reinforce mutual dependency, and therefore a high degree of motivation is needed to cope with the emphasis on boundary work. These projects may be more suited for potential electives or extracurricular activities and focus on the individual students' learning of interdisciplinary collaboration.

This type of project is what the Norwegian University of Science and Technology (NTNU) is practising with experts in teams (Sortland, 2001). The advantages of this type of project are that every single student participates in an interdisciplinary setting, and there is no chance of 'hiding' in disciplinary project teams as it is possible in both the system project and the M-project (defined below).

If a problem reaches a complexity and scale that cannot be handled by one interdisciplinary group alone or within the STEM disciplines, there is a need for a **M-project**, which takes the place of the Megaproject in our framework. The M-project is a mission-driven project (broad in societal vision) and/or Megaproject (broad in scale of long-term impact) across at least two faculties. In the M-project, the problem-solving process is organised via a network of expert teams, and in contrast to the system project, it combines both in-depth STEM and in-depth SSH approaches. Due to the complexity of interaction between multiple teams across STEM and SSH, the relationship between these overall clusters of disciplines can be expected to be loosely coupled. In broad interdisciplinary approaches, technology is not the solution, but part of an interdependent societal system in which knowledge is not borrowed but integrated in an equal dialectic relationship to produce synergy between STEM and SSH.

Although the broad interdisciplinary approaches seem rather complicated in an educational context, this is part of ordinary practice in professional life, as engineers are often required to collaborate with colleagues in, for example, health and safety, marketing, finance, sustainability, etc. When working on more complex and far-reaching problems, such as those addressed by the SDGs, inter-organisational collaboration and partnerships are most likely needed. As in professional life, representatives from different teams or organisations might come together in a coordinating team which might be termed a steering group, a board, or a partnership. Such a coordinating team would obviously include representatives from each team, which underlines the potential of letting students learn the relevant language and practices through participation in a stronger and more interdependent STEM and SSH relationship.

Along with noting the differences between narrow and broad interdisciplinarity, following Klein (2006), it is also important to consider the integration of interdisciplinary results, which can be more or less intertwined (Keestra & Menken, 2016). This means that even though a team or a network of teams may set out to solve problems within the same problem field, the integration of their various knowledge domains is crucial, and as a result, the way the students interact also becomes crucial. The frequency, duration, social bonding, and perceived value of interaction will impact the interdisciplinary integration, and thereby the inter-dependency of the system.

In this project typology, transdisciplinarity is not directly visible. Transdisciplinarity can be defined by the presence of interaction with external partners (which can be academic, non-academic, or both) and of a higher degree of knowledge integration among involved disciplines (Bernstein, 2015). Based on integration of different types of knowledge, new knowledge moving beyond that of any specific discipline can emerge (Gibbons et al., 1994). Interaction with external partners may exist in all types of projects from discipline to M-projects, and thus constitutes a third dimension to potentially integrate into future refinements of the model. The increased integration among disciplines is relevant for research; however, it is far beyond engineering students' learning needs to create new interdisciplinary knowledge domains.

Conclusion and discussion

The purpose of this article is to add greater variety to our conceptual understanding of projects in engineering education. We need an updated language to speak about the variation in educational projects; the scope of the variation discussed in this article incorporates two axes, one describing the number of teams participating in a project, and the other the level of interdisciplinarity. We have applied an action research approach in which researchers have engaged in dialogue and co-creation with educational managers and academic staff throughout the research process. Two iterations within this action research approach have resulted in the development of models for interdisciplinary projects related to disciplinary projects. In the first iteration, we defined four types of projects to encompass the new Megaproject concept which was developed. We collected data to characterise engineering students' experiences in a broad interdisciplinary collaboration. Findings from these studies clearly indicated that the step from disciplinary projects to broad interdisciplinary collaboration in multi-team projects was hard to overcome. As the single project teams remained within their disciplines but had to work on common challenges, there was little opportunity for successful integrative interdisciplinary knowledge constructions; as a result, these projects remained multidisciplinary rather than interdisciplinary.

This led to the second iteration which aimed to identify steppingstones from the disciplinary approach to the broad interdisciplinary approach. In this iteration, we described six project types: discipline, inter-team, domain, system, mixed micro, and M-project. While these project types each have distinct characteristics, there is also significant overlap between them on each of the two axes. It can be hard to distinguish multi – and narrow interdisciplinary approaches, and it can be hard to distinguish inter-team projects from narrow interdisciplinary projects. However, our goal is not to completely isolate the project types from each other, but rather to illustrate possible directions for further developments and formulation of students' learning outcomes.

We collected data for the two newly defined interdisciplinary project types corresponding to the system and the mixed micro project the system and the mixed micro project. To establish the practices associated with these project types, we teamed up with another group of academic staff who had tried to develop more narrow interdisciplinary multi-team projects within one faculty. Furthermore, we established an interdisciplinary project organised as Hackathons in collaboration with a company. These interdisciplinary teams consisted of individual students with both STEM and SSH backgrounds. The findings here confirm earlier findings as the students found the system project meaningful, they learned as much about their own disciplines as other disciplines, and the shared boundary object in terms of a system was a core facilitator of the collaboration.

The six project types are thus defined based on empirical research on the students' experiences. We have learned that teamwork competencies obtained in a disciplinary context cannot be automatically transformed into competencies appropriate to an interdisciplinary setting. The two contexts involve different types of PBL competencies in terms of cognitive collaboration, project management and leadership. The findings show that interdisciplinary teams have difficulties transforming their disciplinary abilities to an interdisciplinary setting as the complexity of the collaborative learning process increases.

First, the findings indicate a need for considerably more research on the facilitation and learning outcomes of interdisciplinary teams compared to disciplinary teams. How can disciplinary teamwork prepare students for more loosely coupled network projects across STEM and SSH? What boundary objects serve to bring the SSH and STEM orientations closer together? We do not have the answer, but we have come closer to understanding the issues involved in these transformation processes. The findings show that interdisciplinary teams need help transforming their disciplinary abilities to an interdisciplinary setting as the complexity of the collaborative learning process increases. This concerns both the cognitive aspects of shared mental models and the meaningfulness and motivation for integrated collaboration. Therefore, it is important to create a progression or provide scaffolding for students to learn to work in increasingly complex contexts so that they are prepared to work on complex problems as engineers. There is a need for new collaborative spaces across teams and disciplines, and if we are to educate the engineers who are going to solve the sustainability problems that were created by previous generations, they will need to learn to collaborate in various contexts and formats and to work in flexible learning organisations and spaces.

The **second** important finding is that the enforcement of interdisciplinarity in loosely coupled systems demands a completely different type of leadership and management competencies from what is required in an individual team setting. When there is an academic teacher helping with the coordination, the learning process is much easier as the students have a facilitator. In some interdisciplinary learning, however, the students should be able to manage the process by themselves as in disciplinary projects. As noted by Bruffee (1995), in comparing collaborative and cooperative learning, one of the challenges with collaborative learning is the non-hierarchical structure, which might create a fuzzier organisation. This poses an even greater challenge in the management and coordination of the projects when we move to network collaboration between teams. A quick fix would be to instruct students on how to collaborate and coordinate between teams and promote a shift to a more collaborative mode of working, but this might compromise opportunities for students to expand their leadership and management competencies. The overarching question is how one can foster leadership and management competencies in a non-hierarchical structure. All potential answers to this question, like letting the teams take responsibility for delegation, project management, conflict management, decision making and reflective skills, become even more complex in the context of a network setting and in more loosely coupled systems.

Katzenbach and Smith (2006) provide a useful framework by distinguishing between 'real teams' and 'potential teams'. In a real team, members are equally committed and hold themselves mutually accountable for shared purposes, goals and working approaches. In contrast, a potential team has no established collective accountability on that level. For a network of teams, one might ask whether it is possible to create a real interdisciplinary team with members across a network of teams from different disciplines to ensure shared commitment in the network. A non-hierarchical structure might not be an interdisciplinary team of managers but rather an interdisciplinary team of what Wenger (2001) calls brokers, who coordinate mutual engagement across teams.

The **third** finding is the new model for disciplinary and interdisciplinary project types. The narrower interdisciplinary approach seems to be a natural steppingstone for students in moving from disciplinary to interdisciplinary projects. There is still research to be done on how to best support students to move from narrow to broad interdisciplinary projects; this project will follow that line of investigation in the coming years. We do not claim that the model we propose here is the only possible model, and we acknowledge its limitations. This model is based on data from one institution with a systemic PBL culture. As researchers, we have been in constant dialogue with the educational managers and academic staff to improve and further develop the interdisciplinary projects under the curricular frameworks in place. Furthermore, it is important to emphasise that the methodology applied also entails its own limitations. Action research is always in flux and in dialogue with partners. The dialogue and interaction can be hard to describe as the researcher co-constructs knowledge together with partners. The qualitative data collected in action research is under multiple pressures, as it must both provide objective and reliable data for research and contribute to effective development within the educational programme in real time.

For future curriculum design, however, we need a framework for differentiating interdisciplinary projects, and the ones currently available are too limited in their approach. The framework proposed in this article is a first attempt to give an understanding of more variation and differentiated learning outcomes from different interdisciplinary projects. The model can hopefully provide input for reflections at other institutions to consider what they are doing and can be doing.

Perspectives

Where do we go from here? There is clearly a need for new collaborative spaces across teams and disciplines, and if we are to educate the engineers who are going to solve the sustainability problems that were created by previous generations, then they need to learn to collaborate in various contexts and formats. There is a need to learn how to work in flexible learning organisations and spaces. However, this raises the related issue of how well we train our students to generate learning out of their experiences with various learning methodologies. We know from the literature that the question of transfer or transformation of skills from one situation to another is complicated. Students might learn to reflect and articulate the learning they have achieved from various practice situations, but have difficulties in recontextualising and applying these experiences in new situations (Dohn, Hansen, & Hansen, 2019; Dohn, Markauskaite, & Hachmann, 2020).

This is an issue for curriculum design, which must adopt as core principles students' competencies to work collaboratively and across disciplines on interdisciplinary problems and academic staff's competencies to facilitate interdisciplinary learning. These are the variables in the curriculum that need to be considered for the success of interdisciplinary projects, and it is evident that curriculum design needs to be aligned with students' experiences and qualifications. Other studies also indicate both that students are developing a positive attitude toward interdisciplinary learning (Gero, 2017) and that there is positive progress in students' learning of interdisciplinary team competencies

(Taajamaa et al., 2014); both observations align with our findings. However, the curriculum design of interdisciplinary projects has to be considered carefully in the context of students' capacity to transform their experiences and competencies from one context to a next. This is the foundation for success of student learning in interdisciplinary contexts, and there needs to be an alignment in the curriculum between learning outcomes and students' experiences (Beddoes, 2020; Borrego & Cutler, 2010). Klaassen (2018) emphasises that in the design process, the level and nature of integration among the disciplines, the alignment between the problem and learning outcomes, and the design of the interdisciplinary curriculum are some of the core variables for a successful outcome. To this list, we can add students' experiences of collaboration and project management.

To respond to the complex challenges addressed in the UN Sustainable Development Goals, we might need a much wider variety of learning methodologies. Most engineering institutions have responded to this need for sustainability by integrating active learning methodologies, such as cooperative or collaborative learning, problem-based learning, project-based learning, design-based learning, or some combination of these suiting the single curriculum, mostly within disciplines. Small-group learning has been widely used, and research has shown that this influences both the learning of content and also the achievement of collaborative competence. However, there is still a need to investigate the more extensive variation in collaborative learning in small groups, in project teams, in networks of teams – both across disciplines or within disciplines. The degree of variation in learning methodologies needs to be increased.

Variation in collaborative learning methodologies – and for different types of projects – will be the foundation for students to experience collaboration in different formats. However, variation is not the only key in developing the engineering curriculum. Variation will create confusion if there is no opportunity for reflection on the similarities and differences between collaborative experiences. Students might experience differences in the collaborative pattern, but to be prepared for collaboration in a work situation they need to learn to reflect on the practices they have experienced so that they are able to articulate these, and they need to learn how they can transfer and transform their learning on collaboration from one situation to another. This might be a new core competency in interdisciplinary engineering education along with technical and scientific knowledge.

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