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Developing a boundary crossing learning trajectory: supporting engineering students to collaborate and co-create across disciplinary, cultural and professional practices

K. P. J. Fortuin [a], Judith T. M. Gulikers [b], Nynke C. Post Uiterweer[c], Carla Oonk[b] and Cassandra W. S. Tho[b]

[a]Environmental Systems Analysis, Wageningen University & Research, Wageningen, Netherlands; [b]Education and Learning Sciences group, Wageningen University & Research, Wageningen, Netherlands; [c]Education and Student Affairs, Wageningen University & Research, Wageningen, Netherlands

ABSTRACT
The competence to work together and co-create with others outside one's own scientific domain, culture or professional practice is a critical competence for engineers to respond to global challenges. In this context, boundary crossing (BC) competence is crucial. We reflect on a university-wide participatory action research educational innovation project for developing and implementing BC in its education, draw conceptual and practical lessons learned and identify success factors. The BC theory and its four learning mechanisms (identification, coordination, reflection, transformation) are introduced and we argue that they provide a solid foundation for BC competence development in courses and curricula. We show that BC can relatively easy be implemented in existing education, yet it is crucial to use experiential types of learning to make this rather abstract concept tangible for both teachers and students. Two key lessons learned for developing BC education are to see BC competence as a generic competence and boundaries as learning opportunities.

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1. Introduction

Engineering education prepares students for a diversity of professional practices in which they are confronted with complex challenges emerging from for example energy transition, sustainable mobility, food production or the implementation of new medical technologies. To address these challenges, future engineers require an array of knowledge and skills, from a solid background in mathematics, physics, technology and design, to professional skills such as project management, writing and presentation (Lantada, Bayo, and Sevillano 2014; Costa et al. 2019). Having those knowledge and skills alone is, however, not enough. To address current and future social, economic, sustainability or medical challenges, engineers need to work together with a wide variety of societal actors such as customers, clients or doctors. They need to be open to new perspectives, willing to enter new unfamiliar domains, and be able to recognise, understand and integrate perspectives and knowledge from various fields. These competencies – among others – are key for collaborating and co-creating new knowledge and innovations in interdisciplinary and international teams in a

CONTACT K. P. J. Fortuin karen.fortuin@wur.nl

productive and efficient way (Van den Beemt et al. 2020; Klaassen 2018). In this paper, we introduce boundary crossing (BC) competence (Akkerman and Bakker 2011) as an overarching concept to indicate the competencies that enable a person to collaborate and co-create in interdisciplinary and international teams. We pose that BC competence is one of the major competencies of future engineers and use the BC theory of Akkerman and Bakker (2011) as a basis to develop engineering education that aims to support and strengthen BC competence development.

This paper captures lessons learned from a university-wide project granted an NWO Comenius Leadership Fellow 2018[1] on implementing BC competence development at course and curricular levels and in the university-wide education policies. This project is grounded in the educational and strategic vision of the university that has educating boundary crossing engineers as one of its focal points. The project is a participatory action research project (Smith, Rosenzweig, and Schmidt 2010), in which conceptual development and practical educational development are continuously intertwined. It built a theoretical fundament for the development of BC competence, designed and partly implemented curricular learning trajectories, and compiled a BC toolbox for and with lecturers, course coordinators, students and management. In this paper, we report and reflect on lessons learned from this participatory educational innovation project that we conducted through a variety of activities with various stakeholders throughout the university. Below, we first pose the importance of BC competence development for engineering education and second expound how BC competence can be developed over the course of a complete engineering education curriculum building on the Akkerman and Bakker's BC theory (2011). Then, we elaborate on the participatory process we followed, describing key participants, activities and data collections. Finally, we reflect on the main lessons learned, both conceptually and practically.

2. Boundaries, boundary crossing and their importance

Addressing complex societal challenges, such as providing access to clean water, increasing the use of solar energy, managing nutrient cycles cannot be achieved by individuals or single agencies alone, neither can this be done within one discipline or culture. The current 'grand challenges' involve various disciplines, societal organisations or actors, and are characterised by value conflicts and uncertainty (Mauser et al. 2013; Lönngren 2019; Van den Beemt et al. 2020). Addressing these challenges in a responsible way requires bridging academia and society, disciplines or study domains, cultures and perspectives. It requires collaborating, learning and co-creating across disciplinary, cultural, or academic and professional practices. Thus, dealing with these grand challenges, requires *boundary crossing* across practices and *boundary objects* to facilitate the collaboration and co-creation (Akkerman and Bakker 2011; Akkerman 2011).

A *practice* is defined as 'a system of actions that have grown historically to achieve certain goals with the means developed to do that. In doing so, certain rules need to be complied and tasks distributed in a certain way' (Bakker and Akkerman 2016, 10). While having goals, rules, methods and ways of working, practices are social systems that are dynamic and develop in interaction and through reflection on action (Schön 1987). One gradually adopts a cultural, disciplinary or professional practice by learning from and in interaction with mature practitioners. When people from various practices meet and interact, they can experience challenges or even tensions, that is, they experience a boundary (Akkerman 2011). A *boundary* is a 'sociocultural difference leading to discontinuity in action or interaction' (Akkerman and Bakker 2011, 133). A boundary is not static and set in stone. Rather, boundaries can be different in different situations. They depend on the relationships of those involved (Akkerman 2011). Engineers may for instance experience a boundary when they collaborate with engineers from another country. Downey et al. (2006) explain how engineers educated in different parts of the world, and who are trained in different ways of solving engineering problems, only realised that they framed and approached engineering problems differently when they collaborated in an international team. During this collaboration, they became aware of boundaries that emerged from the different educational practices in their home countries.

Boundaries can be seen as the difference between 'what is familiar' and 'what is unfamiliar'. They may hamper interaction and collaboration, especially when these boundaries remain implicit and the 'other' perspective is ignored in favour of one's own perspective. Yet, exploring boundaries and trying to understand what is unfamiliar and what hinders the interaction or collaboration provides great learning opportunities. When boundaries are explicated and explored and the 'other' perspective is placed side by side or even integrated within one's own perspective, interaction and collaboration are facilitated and the creation of new, transformative (hybrid) practices or outcomes are made possible (Akkerman and Bakker 2011).

Boundary objects may facilitate dialogical engagement needed to collaborate and co-create across boundaries. Boundary objects are artefacts that are understood in the various practices and meaningful for those involved. They allow to articulate multi-perspectives and meaning and as such facilitate communication across boundaries (Akkerman and Bakker 2011; Star and Griesemer 1989). Examples of boundary objects are documents (e.g. medical record or educational portfolio), online platforms for collaboration, drawings (e.g. architectural blueprint) and conceptual, virtual or physical models (e.g. concept map or matrix) (Borrego et al. 2009; Pennington 2016).

BC can create learning opportunities at the interpersonal and intrapersonal level (Akkerman and Bruining 2016). BC at an *interpersonal level* is about interaction among people from different practices, such as researchers, students or stakeholders with diverse backgrounds, aiming to collaboratively integrate different perspectives into new ideas, practices or innovations. BC at the *intrapersonal level* relates to the personal development of the involved person. By incorporating ideas and new perspectives from other practices, a person's identity, being or behaviour may change. BC at the intrapersonal level influences a person's thinking, doing and communicating (Akkerman and Bruining 2016). Both interpersonal (i.e. co-creation and innovation) and intrapersonal BC (i.e. identity development (Craps et al. 2021, 2022)) are valuable for engineering study programmes (c.f. Borrego and Newswander 2008; Klaassen 2018; Van den Beemt et al. 2020). In sum, boundaries, if explicated and explored, can create great learning opportunities as they can contribute both to the innovation and co-creation of new practices and to the personal development of those involved.

3. Boundary crossing theory

To explain how learning in BC settings happens, Akkerman and Bakker (2011) developed the BC theory. They build their work on the socio-cultural theory of learning (Vygotsky and Cole 1978), that argues that learning happens in social and cultural interactions, inside and outside academia and together with teachers or experts. This theory goes beyond other active learning pedagogies (e.g. problem-based learning or inquiry-based learning) that mainly build on social constructivism and focus on better knowledge retention and the (mainly) cognitive development of students via collaboration and interaction with peers on meaningful assignments in classroom learning (Cattaneo 2017; Hernández-de-Menéndez et al. 2019). The BC theory has originally been applied mostly in school-work crossing settings in which students are faced with bridging academia and professional practice during internships (Akkerman and Bruining 2016). More recently, the BC theory has been applied to sustainability education (Gulikers and Oonk 2019; Oonk et al. 2022), STEM education (Leung 2020), and to train entrepreneurial competence in an interdisciplinary and intercultural setting (Lans et al. 2021). In all instances, BC learning is about (co-)creating something new. The BC theory offers handles for optimising student learning across practices and for using the experienced boundaries as learning opportunities instead of hurdles hampering learning. In this paper, we stretch the BC theory and seek to apply it to the wider context of curricula in engineering education, in particular to programmes that aim to educate students to constructively design or co-create across boundaries of disciplines, cultures and academic practice (Downey et al. 2006).

4. Boundary crossing learning mechanisms used to explore boundaries

Boundaries evoke processes that trigger learning. Learning is meant here in a broad sense as a change in thinking that results from a form of dissonance (Festinger 1957). BC learning may result in better acknowledging and appreciating one's own expertise and perspective, but also in adopting novel approaches or new ways of doing something or co-creating something new. Akkerman and Bakker (2011) introduced four learning mechanisms that are essential heavers for learning across boundaries: *identification, coordination, reflection* and *transformation (I-C-R-T)* (see Figure 1). These mechanisms indicate various ways in which boundaries can be exploited and used as learning opportunities. When used properly, these mechanisms foster learning across the boundaries in the sense of developing new identities (i.e. intrapersonal) or hybrid practices (i.e. interpersonal). Below, we explain the meaning of the four learning mechanisms with a focus on their application in the context of a diverse student group collaborating on an authentic problem commissioned by a non-academic client.

Identification – Identification is becoming aware of one's own expertise as well as of one's own assumptions, values and principles and of how they influence the way one sees and interprets the world. Identification is also about recognising that your way of seeing and interpreting of what is going on can be different from the way others do. As such identification might contribute to being aware of other people's expertise and perspectives. For students, identification is important in the sense that it enables them to better specify who they are, what their expertise is, and what their personal norms and values are in relation to those of others. In a team that collaborates to address a problem, identification involves recognising the team members' perspectives, expertise and assumptions, and identifying what the team is missing in this respect considering the problem at hand.

Coordination – Coordination refers to effectively collaborating. It refers to finding means and procedures to effectively work together in a BC manner. That is, not just dividing the work based on

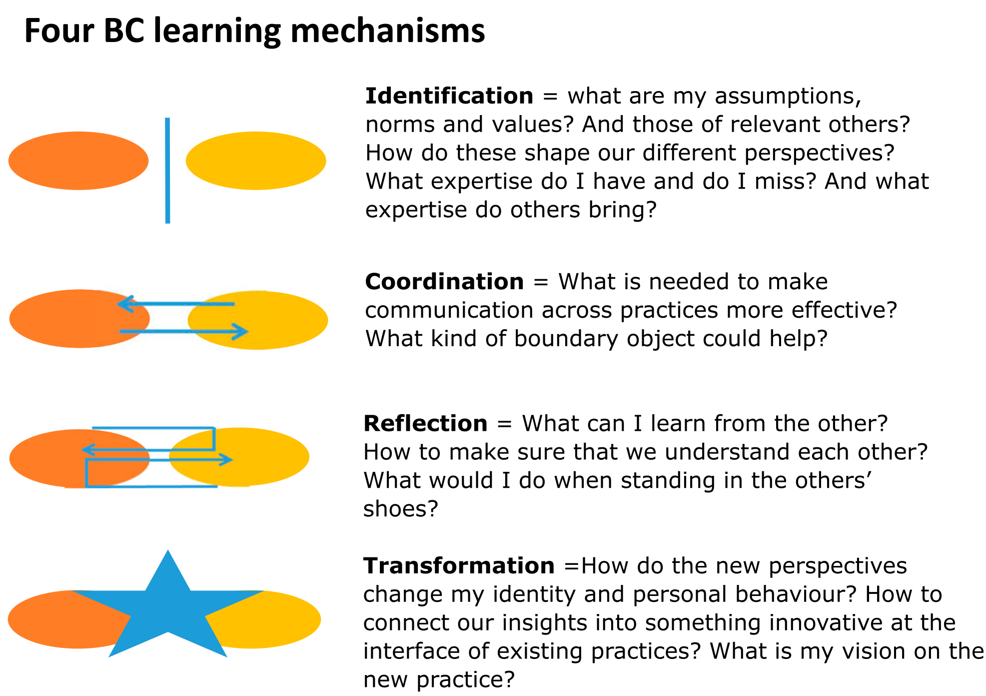


Figure 1. The I-C-R-T boundary crossing learning mechanisms and related questions (based on Akkerman and Bruining 2016).

one's expertise as is often seen in multidisciplinary engineering projects (Borrego and Newswander 2008). Coordination implies that students initiate and organise meetings with relevant people (other students, civil servants, employees of a company or organisation), make working agreements, and seek ways to effectively communicate across various practices/boundaries. Boundary objects could be helpful in this stage.

Reflection – Reflection refers to perspective making and taking. It refers to trying to see the world or one's own practice through the eyes of somebody else, such as a student with a different cultural background, stakeholders involved in the problem at hand, or the client of a consultancy project. Reflection enables students to widen their perspective. It contributes to students' appreciation of a variety of perspectives and practices, their willingness to learn from each other's perspectives, and to support other people's learning.

Transformation – Transformation refers to change in action (behaviour) or practice as a result of being confronted with and utilising a variety of perspectives and expertise. It refers to really doing something new or differently, such as changing personal behaviour because of appreciating and incorporating a new norm, value or perspective. An illustrative example is provided by Lans et al. (2021) who show the impact of a boundary crossing entrepreneurial learning activity on students' risk perception and risk-taking behaviour. In a project team, transformation refers to collaboratively, co-creating new concepts, new routines or procedures, and new, hybrid practices, or innovative solutions (such as new products c.f. Lans et al. 2021).

5. Boundary crossing competence: a generic academic competence

The BC learning mechanisms described above can be incorporated in educational practices where students are confronted with learning across practices of, for example, their disciplinary, cultural or academic practice. The aim of incorporating these kinds of activities within engineering educational programs would be to foster students' development of *boundary crossing competence*. We define BC competence as *the ability to recognize, seek, appreciate and utilize the tensions and challenges that arise when different perspectives and positions come together*. We see BC competence as a generic competence that can be applied in a variety of contexts, inside and outside academia, when faced with a variety of boundaries. We argue that engineering educational programmes should – next to focussing on disciplinary depth – build in BC learning situations within their educational programmes. When these programmes succeed in stimulating students to develop BC competence, these students will be better prepared for crossing the boundaries they will inevitably face in their future career (Craps et al. 2021, 2022).

During their engineering education, students are educated in a particular scientific domain. They learn scientific paradigms, theories, methods and approaches of their own study domain. When they progress in their studies, they usually become more advanced in their specific engineering practice. Often, they don't realise this until they experience challenges in collaborating with people from another disciplinary, cultural or educational practice; until they experience boundaries (c.f., Downey et al. 2006; Fortuin and Bush 2010; Lans et al. 2021). Academics can also experience boundaries when they collaborate with actors from outside academia, when they need to translate scientific knowledge to laypeople, or when they are involved in a policy debate on for instance climate change or vaccination and must defend the importance of scientific knowledge and approaches. Educational programmes should see it as their duty to offer students opportunities to learn to *recognise*, *appreciate* and *use* these boundaries already during their educational programmes.

Within the context of the Comenius Leadership Fellow project, three examples of boundaries have been identified: *disciplinary*, *cultural* and *university-society* boundaries. Obviously, these are not the only boundaries one can encounter. These boundaries have been selected because they explicate a specific context to practice BC competence and are characteristic for our university, that offers interdisciplinary and international life science and engineering programs in which collaboration with partners outside of academia is highly stimulated. These boundaries were identified to

Table 1. Characteristics of boundary crossers.

Good 'boundary crossers'*
- recognise their own identity and qualities and see the limitations of their own perspective and expertise;
- are open and actively seek to contact and learn from other people (i.e. people from other practices, cultures, disciplines or organisations);
- appreciate other people's perspectives, interests, ideas or way of doing, and explore how these differ from their own;
- consider what expertise is needed to successfully perform (in) a project (challenge, assignment or task) and explicate how various expertise, perspectives and interests are used and integrated in a project to deliver a better result;
- see tensions between practices not as something to avoid at all costs, but as a potential source of learning, creativity and change;
- reflect on and learn from the BC experience and encourage other people to do so as well.

*Based on our practical experiences and evaluations of teaching in a variety of BC projects (Fortuin and Bush 2010; Oonk 2016) and findings from literature (e.g. Borrego and Newswander 2008; Downey et al. 2006).

help curriculum management and lecturers to recognise the necessity to address BC in their courses and to include learning activities that trigger to adopt the BC learning mechanisms. We argue that by letting students practice the use of the BC learning mechanisms over time in a variety of learning situations and addressing various boundaries, they become better equipped to deal with any kind of boundaries they will be faced with in their future lives. We expect them to become better 'boundary crossers'. Characteristics of a good boundary crosser are summarised in Table 1.

6. Boundary crossing in educational practice

BC competence development can happen 'anytime anyplace', both in and outside the classroom, in all kinds of (extra)curricular activities such as student challenges (Reymen 2019), but also at study associations or in sports or music clubs, or where diverse students are living together. However, simply being confronted with boundaries, does not mean that students utilise these boundaries to learn, co-create or develop (Van den Beemt et al. 2020). A natural response of most human beings may be to avoid tensions without exploring them. To ensure that all students utilise tensions rather than avoid them, BC competence development should be embedded in their study programmes.

Engineering education already offers a variety of opportunities to practice BC. Often students from various educational backgrounds and from all over the world jointly follow lectures or collaborate in group or lab work. These students may experience boundaries when they collaborate with students from other study programmes, from other nationalities or cultures, or with non-academic actors. Offering students a setting in which a variety of boundaries can be experienced is, however, insufficient to enable fruitful BC learning. Just putting students in an intercultural group and expecting that magic will happen is naive, because it may lead to challenges and frustrations that hamper learning (Popov et al. 2022). Sending students on a field trip will not automatically result in a meaningful BC learning experience as students will not automatically experience the differences between their own perspectives and those of companies, consumers, or other societal actors. *BC competence development requires explicit support and reflection* (Oonk et al. 2022). It needs to be explicated, practiced and trained (Fortuin and van Koppen 2016; Oonk 2016) just like any other competence (e.g. research competence) (Schön 1987).

Previous research identified heuristics of learning environments that evoke BC learning (Fortuin 2015, 141):

- Experience, being involved in addressing a real-life complex issue and applying disciplinary and interdisciplinary methods, techniques and procedures to integrate solution-oriented knowledge.
- Close collaboration in a team of which its members have a diverse (e.g. disciplinary or cultural) background.

- Explicit moments of perspective switching (e.g. specialist, integrator, stakeholder).
- Field work, to integrate classroom-based knowledge in a specific context, to transcend disciplinary knowledge, and to experience the 'complexity' of reality.
- Interaction with stakeholders outside academia and facing the differences in norms and values held by the societal actors and oneself.
- Reflection on the process, the role of science and the role of norms and values in addressing a societal problem.

Within the context of these learning environments, *learning activities* need to be implemented that explicitly address the four BC learning mechanisms (i.e. Identification, Coordination, Reflection and Transformation) and trigger representative BC processes. Figure 1 illustrates the four I-C-R-T learning mechanisms and triggering questions that challenge students to adopt BC processes in their learning. These triggering questions formed the starting point for the design of BC learning activities.

7. Boundary crossing learning trajectories

Mastering BC competence, just as any other competence, is a long-term process that requires practice in a variety of learning situations (van Merriënboer 1997). We, therefore, argue that BC learning activities should not be taught only in solitary courses but be embedded throughout a curriculum: a *BC learning trajectory* is needed to develop BC competence in a systematic way over time (Wijngaards-de Meij and Merx 2018). A learning trajectory consists of: (i) learning outcomes identifying several levels of BC (=*the what*) and (ii) a series of aligned learning activities to which students are exposed to develop towards these levels of BC outcomes (=*the how*). A learning trajectory includes instruction, practice, feedback and assessment. *Alignment* between these curriculum aspects – both within and across courses – is key to develop a competence (Biggs 1996). Such an aligned learning trajectory enables continuous learning and allows a gradual development of competence (Levander and Mikkola 2009). To acquire BC competence, students thus need to be exposed to a variety of BC situations (i.e. different contexts, several types of boundaries), learn to recognise boundaries (of any kind or type), deal with boundaries of increasing complexity (e.g. more boundaries in one situation, more conflicting perspectives) and learn how to handle them in an effective way (e.g. by the design and use of boundary objects) (van Merriënboer 1997).

Figure 2 illustrates such an aligned learning trajectory. This figure shows the journey of a student (the arrow) throughout a study programme to acquire BC competence. During this journey, the student encounters various boundaries and adopts BC learning mechanisms, in a variety of learning activities, and at an increasing level of complexity.

8. The participatory action research process and data collection

This paper reports on a four-year participatory action research (PAR) process (Andriessen 2014; Smith, Rosenzweig, and Schmidt 2010) that aims to innovate engineering education programs to include boundary crossing. A participatory action research process is interactive, iterative and demand-driven. During this PAR project, conceptual development and practical educational innovation (i.e. development of aligned boundary crossing learning activities) were continuously intertwined (Smith, Rosenzweig, and Schmidt 2010). The university-wide project was formally led by the dean of education and strongly aligned with the university's vision and strategy to educate boundary crossers. An interdisciplinary core team of five members representing teachers, educational researchers, and a policy advisor coordinated all activities and fostered ongoing reflection on the learning. Four bachelor programmes were actively involved as pilot programmes (i.e. Food Technology, Animal Sciences, Environmental Sciences, and International Land and Water Management). Teachers and the programme director of these study programmes worked towards designing

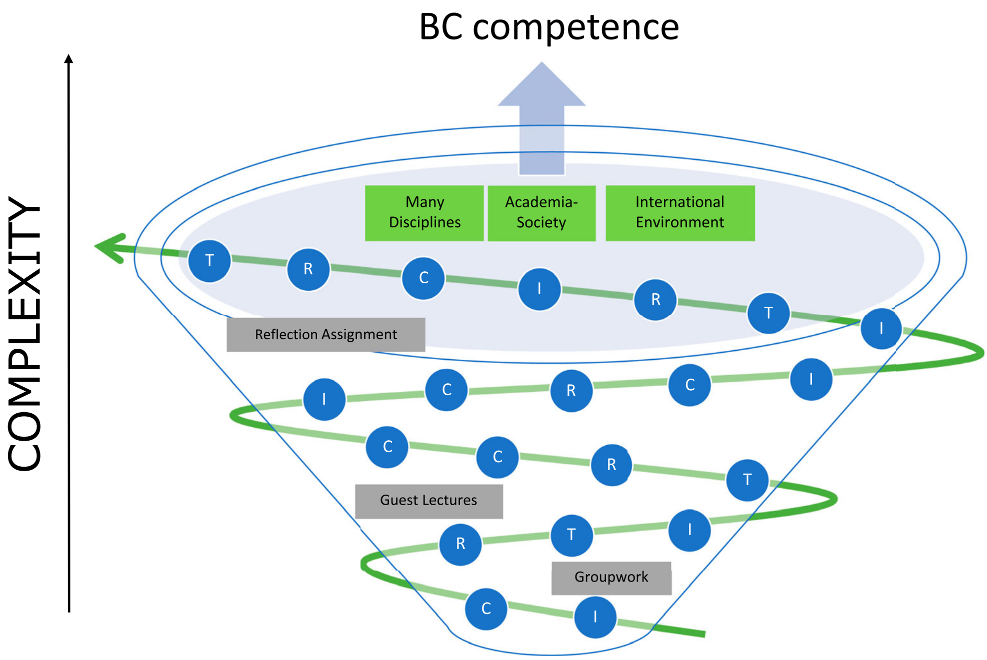


Figure 2. Boundary crossing learning trajectory.

and implementing an aligned set of boundary crossing activities within their courses supported by the BC core team. The BC theory was used as the conceptual fundament that was made instrumental via various collaborative activities (see Table 2), and vice versa, these practical activities provided input for reflection and refinement of the BC theory.

Table 2 describes the most important activities executed by the BC core team throughout the project and the related data collected that allowed us to identify lessons learned on both the product (e.g. developed BC learning activities) and process level (e.g. collaborative process with involved stakeholders towards developing BC in courses and learning trajectories) (Smith, Rosenzweig, and Schmidt 2010). Though not extensive, as many more informal and individual activities and discussions were held in between, this overview aims to underpin the process and make transparent how and what data were collected that were used to deduce lessons learned.

As this overview shows, a variety of activities were conducted, and teachers were often asked to visualise their ideas via posters, Padlets or pre-structured formats in which we – as core team – aimed to make the BC theory instrumental. These visualisations can be seen as boundary objects that stimulated teachers and pilot programmes to explicate *their* understanding of BC in their courses and learning trajectories. They allowed for a more focused and concrete discussion among the pilot programmes about their understandings and differences in understanding of BC. Moreover, these boundary objects helped the BC core team to identify lessons learned and challenges experienced.

9. Developing a BC learning trajectory

To illustrate a BC learning trajectory, we present two examples of BC learning trajectories as developed by two of the BSc pilot programmes participating in the project (Figures 3 and 4). These examples show the learning trajectory by visualising the line of courses that make up the trajectory and per course the addressed boundaries and learning mechanisms. In the annexes, the same courses can be found complemented with the typical BC learning outcomes and examples of learning activities adopted to explicitly address BC (Annex III and IV). Guiding the four pilot programmes,

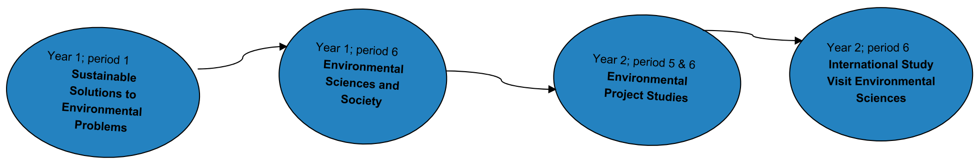
Table 2. Key activities and data collected during the participatory action research (PAR) project.

Activities	Aim	Participants	Data
Presenting the boundary crossing theory and learning mechanisms (*Start of the project*)	Getting stakeholders acquainted with the conceptual framework	Teachers and programme directors of the four BSc programmes	Field notes on the questions asked and discussions raised
Surveying course coordinators and teachers of courses in the pilot programmes (*Beginning of the project*)	Establishing the 'baseline' or state-of-the-art with respect to boundaries present in courses	Course coordinators and teachers of courses in the pilot programmes	Survey responses about the type of boundaries present in courses, and if there was already something being done to address the boundaries
Explicating the boundaries (disciplinary/cultural/society/group work) in all courses of the four BSc programmes (*Beginning of the project*)	Visualising the types of 'boundaries' present in various courses and where opportunities lie for incorporating boundary crossing activities within the programmes	Teachers and programme directors of the four BSc programmes	Visualisations of boundaries present in each of the four BSc programmes
Discussing boundary crossing opportunities per course (*Year 1 of the project*)	Identifying boundaries present in courses, how they are addressed (or not) and discuss ideas with teachers on how they could be addressed more explicitly	Teachers of individual courses of the same study programme identified as potential BC courses	Filled in pre-defined formats per course identifying the boundaries and learning mechanisms present, how they are currently addressed (or not) and how they could be addressed more explicitly
Making posters of initial BC learning trajectory ideas (*After year 1*)	Visualising and sharing the ideas on BC learning trajectories	The four pilot programmes	Four posters by the four pilot programmes and a selection of the key courses within their programme that were identified to be part of their BC learning trajectory
Teacher Crash Course (*Year 2 and 3*)	Developing more concrete boundary crossing learning objectives and activities for courses Reflecting on the alignment between the courses in the learning trajectory using templates to help these processes	Two times two pilot programmes (so, two by two). The programme director + teachers of the identified BC courses participated Teachers went through various activities (course level, programme level, cross-programme level)	Padlet including per course: (i) identified boundaries, (ii) learning objectives, and (iii) ideas for new BC activities Learning trajectory showing the connections between the courses (*objectives and activities*) Posts of teachers' remaining questions or reflections Field notes on the questions and discussions raised
Showing and sharing meeting (*Twice a year*)	Showing lessons learned and remaining questions among the four pilot programmes	Four pilot programmes	Templates filled in with the lessons learned/key insights and questions of the four pilot programmes
Appreciative inquiry interviews with programme directors (*At the end of the project*)	Identifying key lessons learned, insights and questions at programme level, as well as reflecting on the BC project as a whole and how to continue ahead	Programme directors and chairpersons of the programme committee of the four pilot programmes	Transcripts of four interviews
Inspiration meetings university wide (*Yearly*)	Sharing the BC conceptual framework and the educational initiatives developed within the project, but also outside (i.e. other educational programmes that have started to develop BC initiatives on their own)	All university employees interested in BC	Presentations and notes on the various sessions in which teachers presented their BC initiatives and questions and discussions raised in these sessions Blogs were written on all sessions that were made openly available

(*Continued*)

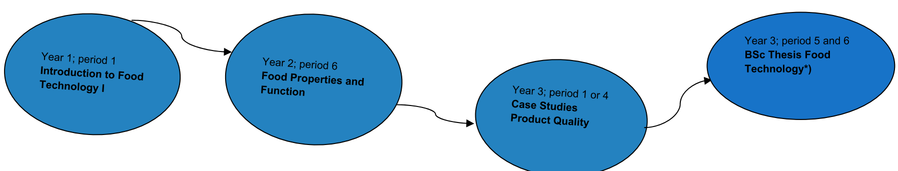
Table 2. Continued.

Activities	Aim	Participants	Data
Bi-weekly meetings (*Throughout the whole project*)	Reflecting on the project, activities, and identifying needs and planning next steps and ongoing identification of lessons learned and conceptual development	BC core team	Minutes of the discussions Various versions of the conceptual framework



Course and its core theme	**Sustainable Solutions to Environmental Problems** *Theme*: Energy transition Students learn that the integration of social science, natural science and technology helps to generate innovative solutions to wicked environmental problems	**Environmental Sciences and Society** *Theme*: Animal Consumption and Production Chain. Students learn how knowledge from different scientific disciplines and stakeholders contributes to creating sustainable solutions.	**Environmental Project Studies** A group research project investigating an environmental issue emanating from professional practice. Attention is paid to the societal aspects of the researched topic, the role of science, and the development of the students' own view on the approach of the issue.	**International Study Visit Environmental Sciences** Dutch students collaborate with students and staff of another university outside the Netherlands on a two-week research project. The main theme (e.g., brownfields, nuclear power) is approached in a multi-disciplinary way.
What boundaries are addressed?	Disciplinary University-Society Cultural	Disciplinary University-Society Cultural	University-Society (between the commissioner's request and university requirements)	Disciplinary Cultural
What BC learning mechanism are addressed?	Identification (of disciplines and stakeholders) Coordination (within the team and with local stakeholders) Reflection (on own (cultural) and stakeholders' perspectives) Transformation (co-creation a sustainable solution)	Identification (of disciplines and stakeholders) Coordination (within the team and with stakeholders) Reflection (on stakeholder perspectives) Transformation (co-creation a sustainable solution)	Coordination (with real life commissioner and stakeholders) Reflection (on societal perspectives)	Identification (of cultural differences) Coordination (with students /faculty abroad) Reflection (on own behaviour and attitude when collaborating in an international setting)

Figure 3. Boundary crossing learning trajectory BSc environmental sciences.



Course and its core theme	**Introduction to Food Technology** Learning to know the disciplinary and societal perspectives related to food technology *Theme:* Ready-to-Eat Salad	**Food Properties and Function** Co-create a food innovation and take into account the consumer perspective	**Case Studies Product Quality** Study a case from industry and suggest product and process quality improvements
What boundaries are addressed?	Disciplinary University-Society Cultural	Disciplinary University-Society Cultural	Disciplinary University-Society
What BC learning mechanism are addressed?	Identification (of disciplines, stakeholders and cultures)	Reflection (on consumer perceptions) Transformation (co-creation of a food innovation)	Coordination (communication with real life stakeholders) Reflection (perspective making and taking on stakeholder assignment and perspectives)

Figure 4. Boundary crossing learning trajectory BSc food technology.

Table 3. Steps to design a BC learning trajectory tailored to a specific curriculum.

1. Stimulate programmes to identify what boundaries graduates need to be able to cross and what kind of skills are crucial for this;
2. Visualise the curriculum and its courses to identify where boundaries are present, what types of boundaries these are (disciplinary, cultural, societal or other) and how they are currently addressed or used in the curriculum albeit implicitly;
3. Show teachers that there are many opportunities to cross boundaries in existing (engineering) courses;
4. Collaboratively identify a number of courses that inherently have BC in them, and bring the teachers of these courses together;
5. Start developing a BC trajectory by collaboratively discussing course learning outcomes, activities and assessment and the possibilities to make BC explicit;
6. Identify alignment within a course (e.g. do the course activities explicitly stimulate the BC learning outcomes?);
7. Place the courses alongside each other to discuss alignment as well as the variety among the courses with respect to BC (i.e. crossing several types of boundaries and the four BC learning mechanisms);

To trigger the explication of all activities and critical reflection in the various steps a template (see Annex I) can be used.

via the various activities described in Table 2, towards the development of their BC learning trajectories, allowed us to identify some guidelines that can help educational programmes work towards a BC learning trajectory (Table 3.)

The BC learning trajectories (Figures 3 and 4) illustrate that students engage in a variety of learning activities that require them to apply one or more of the four BC learning mechanisms, i.e. Identification (I), Coordination (C), Reflection (R) or Transformation (T) in a variety of situations. These situations differ in the *type of boundaries to cross*, the *number of boundaries to cross* and the *complexity of (crossing of) the boundaries*. Both Figures 3 and 4 show that the learning mechanisms are all explicitly addressed several times throughout the curriculum. Intentionally, not all courses address all four I-C-R-T learning mechanisms and the I-C-R-T learning mechanisms are not necessarily experienced in sequential order. Some courses focus on a specific learning mechanism, such as identification, whereas other courses address all four learning mechanisms. In a course, in which students learn to adopt the identification mechanism, they learn their own strengths and weaknesses and to disentangle the qualities that are needed for solving the problem at hand. In a course that addresses all four learning mechanisms, a group of students may for instance be stimulated to start off with envisioning an ideal end product (i.e. transformation) and then to examine how their various disciplinary backgrounds and the use of boundary objects can be used in creating this ideal picture (i.e. identification, coordination and reflection). We are currently implementing the BC learning trajectories in the BSc curricula. In the next section, we will discuss the opportunities and challenges that consequently emerged.

10. Discussion

In our paper, we stressed the importance of BC for engineering education. Both for stimulating the development of important learning outcomes, as well as for fostering a powerful, active, learning process. In terms of outcomes, we argue that BC is important for both fostering innovation, tackling current and future societal challenges as well as for professional identify development. Craps et al. (2021, 2022) emphasised the importance of professional identity development in engineering education and distinguished three career paths for engineering graduates, with a focus on (i) developing new products or technologies, (ii) optimising technology processes or (iii) meeting the needs of the customer. All career paths require BC relevant abilities such as listening to and thinking along with others, acknowledging the feelings and needs of others, and consciously dealing with different backgrounds and interest. The BC perspective posed in our paper can thus be very helpful in thinking about and working on identity development in engineering education.

With the focus on learning and co-creating across disciplinary, cultural and university-society practices, we argue that the BC learning theory adds to other active pedagogies used in (engineering) education (Cattaneo 2017; Hernández-de-Menéndez et al. 2019). Various active learning pedagogies are used, focusing on actively engaging students in the learning process, by, for example, using meaningful, future-oriented cases, problems or projects. Also here, students often learn together via group work or forms of discussions in classroom settings. They mainly aim to, and are found effective for enhancing students' in-depth understanding, knowledge retention and motivation. Some 'more complex' forms of active learning (Hernández-de-Menéndez et al. 2019) can also stimulate the development of competencies as teamwork, problem-solving or critical thinking. Boundary crossing learning can be positioned as a form of active learning. It adds to the currently known pedagogies by positioning the learning even more in real-life, wicked, sustainability challenges that cannot be solved from one perspective (disciplinary, cultural and societal). As such, the focus is not on the – disciplinary – knowledge development of an individual student, but more on the co-creation of new practices as a collective and across practices. Moreover, in boundary crossing learning, students, teachers *and* external stakeholders are learning. Thus, using boundary crossing and its learning mechanisms as a pedagogy, the focus is on equipping students with competencies to use and foster learning with people who differ from themselves. As a result of this learning across practices, new practices and innovations are developed and students can foster their professional identity.

Within this discussion, we reflect on the main lessons learned from this university-wide project for developing and implementing BC courses and learning trajectories in our university of life sciences and engineering education. Firstly, we draw lessons learned at both product level (e.g. BC learning activities or assessments) and education development or process level (e.g. collaboration with teacher teams developing learning trajectories). Secondly, we reflect at the overall project level and identify factors that are considered key for its success. Finally, we identify steps for future work, both for educational practice and theory development.

10.1. Lessons learned at product and process level

An important lesson learned is the power of our gradually developed understanding and conceptualisation of the BC theory and its learning mechanisms as a theory for learning and educational design. During the project, we came to conceptualise BC competence as a *generic* competence, equipping students to learn from and work across any kind of boundary (i.e. stemming from cultural, disciplinary or professional practices), making the theoretical lens applicable to any educational context where 'practices' meet.

When we started to implement the BC theory in education and translated the theory together with teachers into BC objectives, activities, assessments and trajectories, we experienced, however, that both teachers and students find the BC theory rather abstract. Besides, while most teachers immediately recognise BC as crucial for their students, translating this into education is a different cup of tea. Teachers often think 'too big' in the sense of having to change their whole course to implement BC, which paralyzes their actions. Discussing existing learning objectives and learning activities of a course with teachers, brainstorming about minor changes to make these more BC, and providing concrete examples seemed to help specify the rather abstract concept and turn them into action. For example, in a discussion with a lecturer of a course on animal welfare for which students visit several farms, we suggested to add several BC-related questions to the interviews of the farmers and a perspectivist reflection afterwards. These questions and reflections required the students to explicate the farmers' perspectives on animal welfare, and as such made the BC concept tangible. Additionally, based on requests and needs of teachers for examples of BC materials, we developed a toolbox with BC inspiration material, initially built on our own experiences, later elaborated with teachers' own examples. This toolbox includes examples of BC learning outcomes and action verbs, knowledge clips, a range of small – relatively easy to implement – learning activities such as identification assignments, 'standing in the shoes of a stakeholder' or reflection questions tapping into the BC learning mechanisms, and suggestions for assessment activities. All these examples are meant to inspire teachers to think of minor changes within their courses. Thus, an important lesson learned is: make BC tangible by providing examples and making small and very concrete changes in existing assignments or activities.

Another lesson learned related to the abstractness of BC is that using an experiential learning approach seems advisable (Kolb and Kolb 2005). This holds both for teacher and student learning on BC. In academic universities most learning starts with theory ('conceptualisation', Kolb and Kolb 2005), expecting students to be able to use this theory within future assignments or activities. We have learned that for BC, an experiential learning approach for both students and teachers is more fruitful. Confronting students, or teachers, with (real life) engineering challenges that inherently require different perspectives, shows them what BC is, what it means, and why it is important for dealing with these challenges. Such an experience opens students' (and teachers') eyes to the necessity of being able to deal with boundaries in their future careers and can be a starting point to develop this ability within educational activities. For this, we also worked with colleagues involved in teacher professionalisation to conduct a BC training for teachers to enable them to recognise and utilise these boundaries in their own work, and subsequently facilitate the BC competence development in their students.

A challenge we faced in a later stage of the project, was the assessment of BC competence. Questions such as, 'Do all students need to develop BC to the same "level"? Or are some students just more boundary crossers than others?' 'Do we need to assess an *end level*, or should we focus on BC competence *development*?' emerged. The review of Van den Beemt et al. (2020) stresses the underrepresentation of assessment research in interdisciplinary engineering education. In line with Lans, Baggen, and Ploum (2018), we argue that BC development needs more emphasis on formative assessment (i.e. assessment for further learning) rather than on summative assessment (i.e. assessment for grading, selection or decision making). BC assessment requires other *forms* of assessment, other than written exams that university teachers are most familiar with. In co-creation with teachers, we developed ideas for new assessments, such as developing concepts maps throughout a course showing students' new insights gained from new perspectives or teammates, role plays, tracking decision making steps and a BC portfolio. Two lessons learned here are that BC assessment (i) requires a fundamental change in teachers' thinking about assessment (e.g. use formative and qualitative rather than summative and quantitative assessments) and (ii) teachers should be aware to not only think in terms of reflection assignments and self-assessments (Redman, Wiek, and Barth 2020).

Finally, throughout the project, we have learned that possibly the most important gain of BC education in this respect is that students learn to see boundaries as *learning opportunities* instead of annoying or hampering their learning. Many students (and teachers) who collaborate in a multidisciplinary or international team may experience that people with a different background see things differently, but what it means and what the underlying reasons are for seeing things differently remain often elusive whereas – as we explained – being open to and understanding these differences are crucial for cooperation, communication and co-creation.

Attention to interdisciplinarity in engineering education has increased over the last 15 years. Yet it still poses challenges to both teachers and students. Besides, interdisciplinarity is often seen as combining various engineering domains and integrating medical and social sciences is rarely done (Van den Beemt et al. 2020). Engineers are more likely to divide the work in an interdisciplinary team and rely on the contribution of others than to engage in a constructive dialogue to understand what 'the other' contributes to a project (Borrego and Newswander 2008). Borrego and Newswander (2008) make a plea for training engineering students' cognitive flexibility to prepare them for the professional field in which they not only have to focus on technical details but also be aware of and open to societal impacts. Implementing a BC learning trajectory provides great opportunities to train engineers' cognitive flexibility that allow them to see boundaries as learning opportunities fostering co-creation of innovative solutions.

10.2. Lessons learned at the overall project level

At the university-wide project level, we identified four success factors that resulted in a widespread commitment throughout the university and thereby were key to the success of the project. Firstly, the fact that the project was led by the dean of education and grounded in the university's educational and strategic vision, led to a wide ambassadorship and support for the project. The project aimed for BC competence development at the levels of students, teachers and policy makers which enabled the involvement of and cross pollination between all actors across the university. Secondly, the constellation of an interdisciplinary project core team, in which teachers, a policy adviser and educational researchers closely collaborated and met bi-weekly as well as the commitment of four pilot bachelor programmes that signed up for a four-year project to develop towards BC learning trajectories, facilitated successful implementation. Thirdly, a participatory action-research oriented approach (Andriessen 2014; Smith, Rosenzweig, and Schmidt 2010), characterised by zooming in and out, intertwining theory and practice in all steps of the project, and active collaboration among teachers and researchers, was fruitful for both developing educational activities and refining and fuelling our conceptualisation and operationalisation of the BC theory. A final success factor was the bi-annual BC inspiration meetings in which a variety of BC initiatives that were starting up in the university, in various study programmes, were shared. These meetings were key to celebrating successes and inspiring a wider audience.

10.3. Future avenues for research and practice

Our first experiences with students, for example with doing identification assignments, are positive. Students report insights in terms of making their collaboration process much more fruitful, getting to know themselves better and becoming aware of different perspectives on a problem. We are only at the beginning stage of implementing BC in courses, let alone full learning trajectories. A critical question, both relevant to educational and research advancement, is: how to measure BC learning? Measurement of learning across practices, though experimented with, is considered underdeveloped and underdiscussed (Van den Beemt et al. 2020). Evaluating the impact of BC education on students is to be studied in the future.

In our case, especially *transformation* as a learning outcome appeared to be difficult to grasp. Our preliminary insights distinguish between transformation as a *process outcome* and as a *product outcome*. Transformation as a process refers to changed personal behaviour, or identity development, as a result of the effort to incorporate norms, values or perspectives from one practice into the other practices. Transformation as the resulting product of a BC learning refers to a transformative practice, i.e. a new, innovative, hybrid practice across the boundaries of existing practices. Both for teachers and for researchers the learning mechanism transformation needs to be made more tangible to use the learning mechanism's potential in education or to study it as an outcome of BC learning.

We have set many steps in conceptualising and operationalising BC theory as a theory for learning and educational development and applying it to a variety of educational contexts. For bringing the BC theory to a next level, we search to combine the BC theory with other theoretical lenses stemming from interdisciplinary, intercultural or transdisciplinary learning. These other lenses can help to make BC education, and required knowledge and skills, more tangible and concrete, and in turn allow for enriching our conceptual understanding of the BC theory and learning mechanisms. Also, the participatory action research approach characterised by zooming in and out from theory to practice and back to theory again is key to better grasp BC theory and education. We intend to follow up on these ideas by strengthening BC in the teacher training, connecting to similar initiatives and by making use of peer-to-peer learning so that all those involved can inspire each other and cross boundaries.

11. Conclusion

We argued that BC competence is a major and generic competence for engineers, because it enables them to collaborate and co-create with a wide variety of people and can support engineers' professional identity development. Engineering education thus should address BC, open students' eyes to boundaries as learning opportunities, and allow them to develop their BC competence. We explained how the BC theory and its four learning mechanisms provide a solid fundament for BC competence development in engineering education. It can support programme committees, programme directors and lecturers to design BC *learning trajectories*, an aligned set of learning objectives and related learning activities and assessment throughout a curriculum.

The strength of our conceptualisation of the BC theory as a theory for learning and educational development is that it can be seen as an umbrella theory and relatively easy implemented in existing engineering education. While the theory turned out to be rather abstract, we gained experience in making it more tangible by using experiential types of learning, by connecting the theory to individual experiences and applying it to specific contexts teachers and students can relate to. As such we consider the BC theory to be a great fundament to support and strengthen training good 'boundary crossers' crucial for the engineering professional practice. To further BC in practice, we advocate crossing boundaries among lecturers, researchers, policy makers, teacher trainers, study programme management and students.

Note

1. Bregt, A.K. et al. 2017. Application for NWO Comenius Leadership Fellow. Boundary Crossing as the Modus Operandi of Wageningen University, Wageningen University and Research: NWO.

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Notes on contributors

K. P. J. Fortuin is senior lecturer and education coordinator at the Environmental Systems Analysis group at Wageningen University & Research, the Netherlands and involved in international environmental science curriculum development. Her research focusses on improving interdisciplinary and transdisciplinary competence development in environmental-science education in an intercultural context. Besides, she studies the application of environmental systems analysis methodologies and approaches. She is recently appointed as programme director Marine Sciences.

Judith T. M. Gulikers is associate professor at the Education and Learning Sciences group at Wageningen University & Research. Judith is an educational psychologist with a PhD in educational sciences. Her research focusses on assessment at class, course and curriculum level in innovative learning environments (e.g. transdisciplinary – boundary crossing – settings). Her main interest lies in how we can use – formative/sustainable – assessment to make student learning visible and further guide their learning. Judith is also teacher educator.

Nynke C. Post Uiterweer works as a senior policy adviser education at the Dean & Managers office, Education and Student Affairs at Wageningen University & Research. Trained as an irrigation engineer and as a psychologist she's passionate about inter- and transdisciplinary education and research, and sees it as her role to stimulate and enhance boundary crossing learning in Wageningen University education.

Carla Oonk is a researcher, lecturer and education coordinator at the Education and Learning Sciences group at Wageningen University & Research. Carla's research focuses on teaching and learning in transdisciplinary learning environments for which she integrates her backgrounds in Environmental Science (BSc), Land Use Planning (MSc) and Educational Science (PhD). She found the main theoretical foundation for her work in the boundary crossing theory, and aims to further both theoretical insights and practical implications in 'learning with and from "the other" across practices'.

Cassandra W. S. Tho is a researcher and skills trainer at the Education and Learning Sciences group at Wageningen University & Research. Cassandra's research interests lie in the domain of educational innovation in higher education, with a focus on boundary crossing and challenge-based learning.

ORCID

K. P. J. Fortuin http://orcid.org/0000-0002-2754-3713
Judith T. M. Gulikers http://orcid.org/0000-0002-9318-312X

References

Akkerman, S. F. 2011. "Learning at Boundaries." *International Journal of Educational Research* 50 (1): 21–25. doi:10.1016/j.ijer.2011.04.005.

Akkerman, S. F., and A. Bakker. 2011. "Boundary Crossing and Boundary Objects." *Review of Educational Research* 81 (2): 132–169. doi:10.3102/0034654311404435.

Akkerman, S. F., and T. Bruining. 2016. "Multilevel Boundary Crossing in a Professional Development School Partnership." *Journal of the Learning Sciences* 25 (2): 240–284. doi:10.1080/10508406.2016.1147448.

Andriessen, D. 2014. "Praktisch relevant én methodisch grondig? Dimensies van onderzoek in het HBO: Openbare les 2014".

Bakker, A., and S. F. Akkerman. 2016. "Het leerpotentieel van grenzen: een theoretische basis." In *Tussen opleiding en beroepspraktijk : het potentieel van boundary crossing*, edited by S. Beauseart, A. Bakker, I. Zitter, and E. de Bruijn, 9–25. Utrecht: Hogeschool Utrecht.

Biggs, J. 1996. "Enhancing Teaching Through Constructive Alignment." *Higher Education* 32 (3): 347–364. doi:10.1007/BF00138871.

Borrego, M., and Lynita K. Newswander. 2008. "Characteristics of Successful Cross-disciplinary Engineering Education Collaborations." *Journal of Engineering Education* 97 (2): 123–134. doi:10.1002/j.2168-9830.2008.tb00962.x.

Borrego, M., C. B. Newswander, L. D. McNair, S. McGinnis, and M. C. Paretti. 2009. "Using Concept Maps to Assess Interdisciplinary Integration of Green Engineering Knowledge." *Advances in Engineering Education* 1 (3): 1–25.

Cattaneo, K. H. 2017. "Telling Active Learning Pedagogies Apart: From Theory to Practice." *Journal of New Approaches in Educational Research* 6 (2): 144–152. doi:10.7821/naer.2017.7.237.

Costa, A. R., M. Ferreira, A. Barata, C. Viterbo, J. S. Rodrigues, and J. Magalhães. 2019. "Impact of Interdisciplinary Learning on the Development of Engineering Students' Skills." *European Journal of Engineering Education* 44 (4): 589–601. doi:10.1080/03043797.2018.1523135.

Craps, S., M. Pinxten, H. Knipprath, and G. Langie. 2021. "Exploring Professional Roles for Early Career Engineers: A Systematic Literature Review." *European Journal of Engineering Education* 46 (2): 266–286. doi:10.1080/03043797.2020.1781062.

Craps, S., M. Pinxten, H. Knipprath, and G. Langie. 2022. "Different Roles, Different Demands. A Competency-based Professional Roles Model for Early Career Engineers, Validated in Industry and Higher Education." *European Journal of Engineering Education*, 1–20. doi:10.1080/03043797.2021.1889468.

Downey, G. L., J. C. Lucena, B. M. Moskal, R. Parkhurst, T. Bigley, C. Hays, B. K. Jesiek, et al. 2006. "The Globally Competent Engineer: Working Effectively with People Who Define Problems Differently." *Journal of Engineering Education* 95 (2): 107–122. doi:10.1002/j.2168-9830.2006.tb00883.x.

Festinger, L. 1957. *A Theory of Cognitive Dissonance*. California: Stanford University Press.

Fortuin, K. P. J. 2015. "Heuristic Principles to Teach and Learn Boundary Crossing Skills in Environmental Science Education." PhD. Wageningen University.

Fortuin, K. P. J., and S. R. Bush. 2010. "Educating Students to Cross Boundaries Between Disciplines and Cultures and Between Theory and Practice." *International Journal of Sustainability in Higher Education* 11 (1): 19–35. doi:10.1108/14676371011010020.

Fortuin, K. P. J., and C. S. A. van Koppen. 2016. "Teaching and Learning Reflexive Skills in Inter- and Transdisciplinary Research: A Framework and its Application in Environmental Science Education." *Environmental Education Research* 22 (5): 697–716. doi:10.1080/13504622.2015.1054264.

Gulikers, J., and C. Oonk. 2019. "Towards a Rubric for Stimulating and Evaluating Sustainable Learning." *Sustainability* 11 (4): 969. doi:10.3390/su11040969.

Hernández-de-Menéndez, M., A. Vallejo Guevara, J. C. Tudón Martínez, D. Hernández Alcántara, and R. Morales-Menendez. 2019. "Active Learning in Engineering Education. A Review of Fundamentals, Best Practices and Experiences." *International Journal on Interactive Design and Manufacturing (IJIDeM)* 13 (3): 909–922. doi:10.1007/s12008-019-00557-8.

Klaassen, R. G. 2018. "Interdisciplinary Education: A Case Study." *European Journal of Engineering Education* 43 (6): 842–859. doi:10.1080/03043797.2018.1442417.

Kolb, A. Y., and D. A. Kolb. 2005. "Learning Styles and Learning Spaces: Enhancing Experiential Learning in Higher Education." *Academy of Management Learning & Education* 4 (2): 193–212. doi:10.5465/amle.2005.17268566.

Lans, T., Y. Baggen, and L. J. L. Ploum. 2018. "Towards More Synergy in Entrepreneurial Competence Research in Entrepreneurship Education." In *A Research Agenda for Entrepreneurship Education*. Cheltenham: Edward Elgar Publishing.

Lans, T., R. Lubberink, L. Ploum, M. Ammann, and S. Gondwe. 2021. "Entrepreneurial Learning at the Boundary: How to Learn from a Local Cheese Maker." *Entrepreneurship Education and Pedagogy* 4 (3): 527–548. doi:10.1177/2515127420925015.

Lantada, A. D., A. H. Bayo, and J.d.J. M. Sevillano. 2014. "Promotion of Professional Skills in Engineering Education: Strategies and Challenges." *International Journal of Engineering Education* 30 (6): 1525–1538.

Leung, A. 2020. "Boundary Crossing Pedagogy in STEM Education." *International Journal of STEM Education* 7 (1): 15. doi:10.1186/s40594-020-00212-9.

Levander, L. M., and M. Mikkola. 2009. "Core Curriculum Analysis: A Tool for Educational Design." *The Journal of Agricultural Education and Extension* 15 (3): 275–286. doi:10.1080/13892240903069785.

Lönngren, J. 2019. "Wicked Problems in Engineering Education: Preparing Future Engineers to Work for Sustainability." *Environmental Education Research*, 1–2. doi:10.1080/13504622.2019.1639038.

Mauser, W., G. Klepper, M. Rice, B. S. Schmalzbauer, H. Hackmann, R. Leemans, and H. Moore. 2013. "Transdisciplinary Global Change Research: The co-Creation of Knowledge for Sustainability." *Current Opinion in Environmental Sustainability* 5 (3–4): 420–431. doi:10.1016/j.cosust.2013.07.001.

Oonk, C. 2016. "Learning and Teaching in the Regional Learning Environment Enabling Students and Teachers to Cross Boundaries in Multi-Stakeholder Practices." PhD. Wageningen University & Research.

Oonk, C., J. Gulikers, P. den Brok, and M. Mulder. 2022. "Stimulating Boundary Crossing Learning in a Multi-stakeholder Learning Environment for Sustainable Development." *International Journal of Sustainability in Higher Education* 23 (8): 21–40. doi:10.1108/IJSHE-04-2021-0156.

Pennington, D. 2016. "A Conceptual Model for Knowledge Integration in Interdisciplinary Teams: Orchestrating Individual Learning and Group Processes." *Journal of Environmental Studies and Sciences* 6 (2): 300–312. doi:10.1007/s13412-015-0354-5.

Popov, V., D. Brinkman, K. P. J. Fortuin, R. Lie, and Y. Li. 2022. "Challenges Home and International Students Face in Group Work at a Dutch University." *European Journal of Engineering Education* 47 (4): 664–678. doi:10.1080/03043797.2022.2044762.

Redman, A., A. Wiek, and M. Barth. 2020. "Current Practice of Assessing Students' Sustainability Competencies: A Review of Tools." *Sustainability Science*. doi:10.1007/s11625-020-00855-1.

Reymen, I. M. M. J. 2019. *Collaborate with Social and Economic Impact*. Eindhoven: Technische Universiteit Eindhoven.

Schön, D. A. 1987. *Educating the Reflective Practitioner: Toward a new Design for Teaching and Learning in the Professions*. San Francisco: Jossey-Bass.

Smith, L., L. Rosenzweig, and M. Schmidt. 2010. "Best Practices in the Reporting of Participatory Action Research: Embracing Both the Forest and the Trees 1Ψ7." *The Counseling Psychologist* 38 (8): 1115–1138. doi:10.1177/0011000010376416.

Star, S. L., and J. R. Griesemer. 1989. "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology." *Social Studies of Science* 19: 387–420. doi:10.1177/030631289019003001.

Van den Beemt, A., M. MacLeod, J. Van der Veen, A. Van de Ven, S. van Baalen, R. Klaassen, and M. Boon. 2020. "Interdisciplinary Engineering Education: A Review of Vision, Teaching, and Support." *Journal of Engineering Education* 109 (3): 508–555. doi:10.1002/jee.20347.

van Merriënboer, J. J. G. 1997. *Training Complex Cognitive Skills: A Four-Component Instructional Design Model for Technical Training*. Englewood Cliffs, NJ: Educational Technology.

Vygotsky, L. S., and M. Cole. 1978. *Mind in Society: Development of Higher Psychological Processes*. London: Harvard university press.

Wijngaards-de Meij, L., and S. Merx. 2018. "Improving Curriculum Alignment and Achieving Learning Goals by Making the Curriculum Visible." *International Journal for Academic Development* 23 (3): 219–231. doi:10.1080/1360144X.2018.1462187.

Appendices

Annex I: Questions to trigger programme committees, programme directors and lecturers about boundary crossing within their curricula and support the development of a learning trajectory

1. *Identifying boundaries*

- What boundaries do you expect your graduates to be able to cross? And thus, what boundaries should your students be confronted with during your study programme?
- Which boundaries do you want your students to practice crossing?
- Does your programme aim at developing BC at interpersonal or at intrapersonal level, or at both?

2. *Doing an inventory of current BC experiences in a curriculum:*

- Where in your study programme are boundaries present?
- Are these boundaries utilized as learning opportunities?
- Are explicit learning activities used to help students crossing the boundaries? If so, which ones?
- Is BC instructed, practised, is feedback given, is BC assessed?

3. *Selecting courses that will explicitly address the I-C-R-T learning mechanisms:*

- Which courses are suitable for *instructing* students on BC and BC learning mechanisms?
- Which courses are suitable to develop BC at interpersonal level? Which courses are suitable to develop BC at intrapersonal level?

4. *Developing new learning outcomes and learning activities that explicitly address the I-C-R-T learning mechanisms, including instruction, practice, feedback and assessment.*

- How can you change existing learning activities to make more explicit use of already present boundaries?
- What new learning activities can you design?

Once these questions are addressed, learning activities and assessment tools need to be developed. One of the outcomes of the Comenius project is the development of a toolbox for learning activities and assessment tools. Some examples are presented in Annex II. More can be found at https://edusources.nl/, select Boundary Crossing Community.

Annex II: Examples of boundary crossing learning outcomes and activities

To make BC more tangible, this section will display some exemplary BC-learning outcomes, learning activities and learning trajectories developed in various Bachelor and Master programmes of our University.

Exemplary learning outcomes

BC learning outcomes are often, and can easily, be linked to the more content related learning outcomes of a course. The examples below show a variety of learning outcomes. After every learning outcome we will show 1) the name of the programme, 2) the year of study, 3) the addressed BC learning mechanism(s), and if applicable 4) the type of boundary at stake.

- Know what is interdisciplinarity in the food domain and recognize this for different phenomena (BSc Food Technology, year 1/period 1, identification, disciplinary boundary);
- Integrate theoretical and practical knowledge from various food science disciplines while considering the consumer perspective as well (BSc Food Technology, year 1/period 6, identification/transformation, disciplinary and university-society boundary);
- Communicate project progress with various stakeholders (BSc Food Technology, year 1/period 6, coordination/reflection, university-society boundary);
- Assess and analyse land use and water management issues from different academic and societal perspectives and bring these together (BSc International Land and Water management, Year 1/period 1, reflection/transformation, all kind of boundaries);
- Create additional value by combining biobased disciplines thus to apply an interdisciplinary approach (MSc Biobased Sciences, Year 2, identification/reflection/transformation, disciplinary boundary);
- Work as part of a multi-disciplinary and multicultural team and value the contribution of different perspectives in designing solutions for complex (environmental) problems (MSc Environmental Sciences, year 1/period 6, identification/coordination/reflection, disciplinary and cultural boundary).

Exemplary learning activities

We can also make BC more tangible in learning activities. Below we present some learning activities that can be integrated in any kind of course. They are described independent from a specific context or educational program. The table shows what type of boundaries are crossed, possible variations to the learning activity and the addressed BC learning mechanism(s).

Title	Core of the activity	Boundaries addressed	Possible variation /addition
Debating different perspectives	Assign students roles of different stakeholders from who's viewpoint they participate in the debate	University-society Possibly different disciplinary perspectives	Let students prepare their own stakeholders' perspectives more or less thoroughly with/without guiding questions BC-Learning mechanism: Identification, Coordination & Reflection_
Exploiting cultural group diversity in a poster market	Take a controversial topic relevant to the course (e.g., animal welfare, Palm oil, water conservation) Let students from different countries/cultures explicitly elaborate on the topic from their national & cultural perspective. Every student prepares a poster. In a poster market session students share perspectives. After the market intercultural groups develop a shared poster showing the topic from all different perspectives.	Cultural and international	Provide guiding questions to be addressed on the poster Let individual students elaborate their own poster with new insights gained from the other posters. Ask individual students to express (orally or verbally) how their own national/cultural perspective is challenged by the others: how is your own opinion on the topic changed? BC-Learning mechanism: Identification, Coordination & Reflection
Including multi-perspectivity in field visits and excursions	Offer students a list of critical questions to be asked to the societal stakeholder they visit to identify the stakeholder's perspective on a course relevant topic	University-society	A. Prepare: Let students first explicate their own perspective on the topic: What do they currently know about this issue? How do they feel about it? B. Prepare: Let students individually or in groups prepare a list of critical questions to ask the societal stakeholder to grasp their perspective C. Afterwards: Let students together visualise trade-offs between identified perspectives (including their own) BC-Learning mechanism: Identification, Coordination, Reflection_
The BC portfolio	Students reflect on their own experience and developments regarding interdisciplinarity. They will create a portfolio with reflection papers written at X moments during the study programme Students have to defend their reflection in a final interview.	Disciplinary	Other boundaries, relevant for the study program, can be integrated BC-learning mechanisms: reflection, (intrapersonal) transformation
Developing a concept map using colour coding	Student groups collaboratively develop a concept map on certain topics using colour coding: Step 1: individual concept map (blue pen) Step 2: elaborate 1 individual map with additions form other maps (red pen) Step 3: let students study the topic from a certain perspective (in books, articles, internet) Step 4: further elaborate the map with the theoretical insights (green pen)	Depending on the assigned perspectives in step 3.	A. Let students identify different disciplinary influences in their own perspective in step 1 B. let student draw an individual concept map afterwards, showing their (changed) own perspective BC-Learning mechanism: Identification, Coordination & Reflection

Annex III: Boundary Crossing Learning Trajectory BSc Environmental Sciences

Course and its core theme	**Sustainable Solutions to Environmental Problems** Theme: Energy transition Students learn that the integration of social science, natural science and technology helps to generate innovative solutions to wicked environmental problems	**Environmental Sciences and Society** Theme: Animal Consumption and Production Chain. Students learn how knowledge from different scientific disciplines and stakeholders contributes to analysing, solving, and preventing environmental problems, and to creating sustainable solutions.	**Environmental Project Studies** A group-wise research project investigating an environmental issue emanating from professional practice. Due attention is paid to the societal aspects of the researched topics, the role of science, and the development of the students' own view on the approach of environmental problems.	**International Study Visit Environmental Sciences** Dutch students collaborate with students and staff of another university outside the Netherlands (Ukraine, Estonia) on a two week research project. The main theme (restoration of semi-natural habitats, brownfields, nuclear power) is approached in a multi-disciplinary way.
What boundaries are addressed?	Disciplinary University-Society Cultural	Disciplinary University-Society Cultural	University-Society (between the commissioner's request and university requirements)	Disciplinary Cultural
What BC learning mechanism are addressed?	Identification (of disciplines and stakeholders Coordination (within the team and with local stakeholders) Reflection (on own (cultural) and stakeholders' perspectives) Transformation (co-creation a sustainable solution)	Identification (of disciplines and stakeholders) Coordination (within the team and with stakeholders) Reflection (on stakeholder perspectives) Transformation (co-creation a sustainable solution)	Coordination (with real life commissioner and stakeholders) Reflection (on societal perspectives)	Identification (of cultural differences) Coordination (with students /faculty abroad) Reflection (on own behaviour and attitude when collaborating in an international setting)
Example of a BC learning objectives of the course (as part of the complete set of learning objectives)	1. *explain that environmental problems need to be approached from different natural and social scientific disciplines;* 2. *analyse an environmental problem related to real-world issues and stakeholders' perspectives;* 3. *synthesise different types of knowledge and information to develop transformative sustainable solutions;* 4. *identify how cultural perspective influence one's role in the group and one's take on environmental issues.*	1. *analyse environmental problems triggered by the Animal Consumption and Production Chain and the underlying societal trends, using visions, knowledge and methods from different (scientific) disciplines.* 2. *evaluate how technological, natural and social sciences contribute to solve and prevent complex environmental problems.* 3. *collaborate in a multidisciplinary and multicultural team acknowledging various perspectives* *4. Explain what the specializations of the study program are […] and what are the possible professions.*	1. *Understand the societal context of environmental research and the societal backgrounds of environmental problems;* 2. *collaborate in a group and have developed the knowledge and skills required to reflect on and evaluate this collaboration;* 3. *initiate and sustain contacts with their supervisor and client.* 4. contribute to strategies to address an environmental or sustainability issue for an external client.	1. *evaluate (conceptualize) multiple dimensions of an environmental problem abroad;* 2. *collaborate in a team on a joint project, using inter- and intrapersonal skills, in consultation with experts from abroad, such as faculty members and students from the host institution and relevant stakeholders;;* 3. *Synthesize their experiences and lessons learned in international research collaboration (and a new cultural environment).*
Example of a BC learning activity in the course	*Excursion*: students visit different places and persons (municipality, NGO, inhabitants) and reflect on the role and perspectives of these persons and their own. *Group assignment* to collaboratively (i) develop a clear problem definition,	*Lectures* by lecturers from different chair groups (social, natural sciences and technology) sharing state of the art knowledge in their field and its relation to the central theme of the course. *Excursions* to various farms, a nature restoration project, and a regional	Supervised *group research project* for a non-academic commissioner: writing a research proposal based on the problem as identified by the commissioner; collecting and analysing data; reporting orally and in writing.	*Guest lectures* provided by experts from various universities. Students are encouraged to prepare for these lectures and engage in discussions with the experts. *Excursions* to explore the study area and surroundings and learn about

highlighting the interrelated role of technology, people, the environment, and various stakeholders; (ii) analyse the problems from various perspective; (iii) to develop a solution (synthesis); (iv) reflect on the solution and its contribution to the problem. Group report and oral defence of key features of the report are assessed.	government. Students are expected to empathize with and prepare questions for the people they will meet prior to the visit. *Group assignment* to provide an overview of environmental problems caused by the production and consumption of meat and potential sustainable solutions whereby taken into account the interests, perspectives and considerations of the main stakeholders resulting in a report and oral presentation. *Individual assignment* to orient on study and job perspectives after graduation.	Collaborative *reflection on the societal context* of the research, to (i) explain the relationship with overarching environmental debates; (ii) clarify the societal context and impact of environmental research; (iii) outline values and interests that may affect the methodology and outcomes of research; (iv) express a personal view on the problem studied and the interventions proposed to address this problem.	ongoing research at home and abroad. *Intercultural competence training* to get insights in cultural differences. *Group research assignment* in an intercultural team. Different nationalities and backgrounds are mixed to enhance the intercultural learning experience. *Reflection*: student have to reflect throughout the course on their own behaviour, attitude as well as actual steps taken to overcome challenges, and write a reflection assignment. Assessment is on both content (presentation, poster) and process (participation, engagement, and the reflection assignments).

Annex IV: Boundary Crossing Learning Trajectory BSc Food Technology

Course and its core theme	**Introduction to Food Technology** Learning to know the disciplinary and societal perspectives related to food technology Theme: Ready-to-Eat Salad	**Food Properties and Function** Co-create a food innovation and take into account the consumer perspective	**Case Studies Product Quality** Study a case from industry and suggest product and process quality improvements
What boundaries are addressed?	Disciplinary; University-Society; Cultural	Disciplinary; University-Society; Cultural	Disciplinary; University-Society
What BC learning mechanism are addressed?	Identification (of disciplines, stakeholders and cultures)	Reflection (on consumer perceptions) Transformation (co-creation of a food innovation)	Coordination (communication with real life stakeholders) Reflection (perspective making and taking on stakeholder assignment and perspectives)
BC learning objectives of the course (italic, red objectives as part of the complete set of learning objectives)	1. *know and/or understand the basic elements and concepts of the scientific disciplines that span food technology;* 2. know the disciplinary frameworks that are constructed from the basic elements and concepts; 3. know and apply the knowledge on a defined set of basic phenomena to explain and control properties of foods, within the context of one discipline; 4. understand and apply this understanding how to manipulate these phenomena; 5. *recognize which phenomena of different disciplines are relevant to explain and control properties of foods, and point out their interrelationship(s) (i.e. identify interdisciplinarity)* 6. use ICT-software programs; *7. have insight in the overall context in which the food industry and its stakeholders operate.*	1. *integrate theoretical and practical knowledge from various food science disciplines taking into account the consumer perspective as well;* 2. understand the implications of changes in food product ingredients or processing on the final product properties; 3. understand the effect of chosen processing on food properties and -quality; 4. understand how food quality can be determined with appropriate sensorial and instrumental approaches; 5. understand the methodology and use of modern analytical techniques; 6. *understand the ethical issues involved in innovation of food products and to apply this knowledge in practical situations;* 7. work in small groups and to plan, carry out and evaluate experiments to make an innovated food product and to present the results.	1. *apply basic knowledge from various disciplines in food technology to define and improve food product quality;* 2. *translate a question from society (company, institute, start-up, government) into a feasible scientific research project;* 3. search, understand and use scientific literature; 4. *work in a team on a joint research project, using inter- and intrapersonal skills* 5. *communicate project progress with various stakeholders* 6. scientifically report and present project results
BC learning activity (and/or assessment activity) in the course	Students visit a company and get the assignment to prepare for a set of questions to be asked to the company staff on stakeholders involved, stakeholders' roles, perspectives and mutual relations, job opportunities etc. Students report their findings as part of the final assignment for the course (including a visualisation of the stakeholder analysis and reflection on	As part of their innovation assignment, students investigate the consumer perception of their innovation in a broad sense (e.g. health; cultural; economic). They interview real life consumers and apply consumer perceptions into their innovation. In their final reports, students are required to describe how the identified consumer	Real life commissioner introduces the case to the students. During the case study, students contact the commissioner and other stakeholders (identified by themselves) to discuss their progress and findings. Finally they present the results to the commissioner. Commissioner and stakeholders are stimulated to translate the findings into

	suitability of various job positions, and how their view on job opportunities developed over time during the course). Lecture on intercultural communication and related workshop on finding out intercultural perspectives on various topics. Additional exam questions: which disciplines are integrated in the Ready-to-Eat Salad? Do you consider this set of disciplines to be complete? Why yes/no? Which other disciplines should actually be integrated?	perspectives have been used/applied in their innovations.	follow up assignments (for these or other students). Students write reflections, both mid-way and at the end on how they assessed the commissioners feedback and how they used the feedback in their further work.