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# Student learning experiences in mathematics-oriented challenge-based courses

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*Challenge-Based Education (CBE) has become an important innovative approach to student-centred engineering education. We have studied what students perceived to learn in three mathematics-oriented CBE courses, and how the different resources, which the students reported to have used, were related to their work in the CBE environments. We drew on literature regarding (a) Challenge-based education and (b) the role of resources in students' learning processes. A case study approach was used (with the three courses as cases) involving qualitative data collection strategies. Comparing the cases, we found that the student learning experiences were in line with the general aims of CBE. Student progress was fostered by the use of different resources, depending on the set-up of the courses and the challenges.*

*Keywords: Student learning experiences, challenge-based education, student use of resources.*

## Introduction

Universities of technology are developing innovative learning environments to create more student-centred forms of engineering education (Pepin & Kock, 2021). An aim of these innovations is to make engineering education more relevant and engaging for students by enabling them to contribute to the solution of societal problems, often in a collaboration between industry and universities. In this paper we focus on one of these innovative approaches: Challenge-Based Education (CBE), a term which in this paper can refer to both teaching and learning processes. In CBE, the acquisition and production of disciplinary knowledge and the development of professional competencies (e.g., problem resolution, design capacity, ethical awareness, and multidisciplinary collaborative work) are expected to go hand in hand. Groups of students are given a challenge, which is often connected to one of the 'grand challenges' in society and is provided by a stakeholder from an external organization (e.g., a company or a research institute). Based on the challenge, students identify a problem they want to work on, and they develop their knowledge and competences by collaboratively developing a solution to the real-life problem, generally in the form of a working prototype or proof of concept. Often this takes place in a multidisciplinary setting. However, as CBE is a relatively new approach, there are still questions with respect to its implementation in engineering education (Gallagher & Savage, 2020). In CBE courses involving mathematics, research is needed to identify the affordances and constraints of the approach regarding the development of professional competencies and disciplinary knowledge, and to find out how students can be successfully supported. The interaction with resources is an essential factor contributing to learning processes (Trouche, 2004), in traditional, as well as in innovative student-centred forms of education such as CBE (Pepin & Kock, 2021). In this study, we have zoomed in on the students' perspective, in order to understand how CBE "worked" for them, that is, what students perceived to learn in CBE courses and in which ways the use of resources, according to the students, contributed to their learning.

We ask the following research questions:

RQ1: What did the students perceive to learn in mathematics related CBE courses?

RQ2: How were the different resources, which the students reported to have used, related to their work in the CBE environments?

To answer the research questions, we have studied three selected cases of mathematics related CBE courses at a university of technology in the Netherlands.

## **Theoretical Framework**

We draw on literature regarding (a) the pedagogy of CBE, and (b) the role of resources in students' learning processes.

### **Challenge-Based Education**

CBE falls under the umbrella of inquiry-based education (Martin et al., 2007). No generally agreed upon definition of CBE exists (Gallagher & Savage, 2020), but CBE learning environments are said to offer learning experiences “where the learning takes place through the identification, analysis and design of a solution to a sociotechnical problem” (Malmqvist et al., 2015, p. 87). Depending on the context, other characteristics may be present in the learning environment, to a greater or lesser extent, for example, collaborative teamwork; multi-disciplinarity; environmental, social and economic sustainability; or, interaction with stakeholders. The characteristics of a particular learning environment should be considered holistically when determining whether it may be described as CBE (van den Beemt et al., 2023). It is claimed that CBE is motivating for students, because of the real-world character and the relevance of the challenges, and the autonomy they have. Moreover, students are said to acquire disciplinary knowledge as well as professional competences while interacting and collaborating with stakeholders (Gallagher & Savage, 2020). In CBE, the tutor's role changes from the traditional role of a knowledge provider to that of a coach (in this paper the term *tutor* includes lecturers and teaching assistants).

### **The lens of resources**

In CBE, course organizers only provide a limited amount of resources to the students. This is partly due to the openness of the challenges, partly to the pedagogy of inquiry which expects students to look for resources themselves. To solve their problem, students thus also depend on multiple self-selected resources. According to the Instrumental Approach (Trouche, 2004), two simultaneous processes take place when students work with resources: *instrumentation*, a process in which the affordances of resources influence student practice and learning; and *instrumentalization*, a process in which students adapt the resources according to their own needs.

We distinguish different categories of resources (Pepin & Kock, 2021): curriculum resources (e.g., textbooks, curricular guidelines, an electronic learning environment), social resources (e.g., conversations with tutors, peers and stakeholders), cognitive resources (e.g., mathematical concepts and techniques), and general resources (e.g., software, search engines or other digital resources). Pepin and Kock (2021) have suggested that particular resources, such as feedback from tutors and

interactions with stakeholders, gain importance in student-centred learning environments as compared to more traditional teacher-centred environments.

## **Context**

The study took place at a Dutch university of technology which offers educational programs in science, core engineering studies and social engineering studies. The university is in the process of introducing CBE as a core educational strategy, with the aim to educate future engineers who have a deep understanding of their discipline and are able to work collaboratively on complex problems in multidisciplinary settings. For the study, we selected three courses, based on the following criteria: (a) presence of CBE characteristics; (b) participation of Applied Mathematics students; (c) presence of mathematical content; (d) in different years of the university curriculum; (e) voluntary participation of tutors and students. The three selected courses all involved mathematical modelling:

(1) An elective course on the Physics of Social Systems (PSS) open to students from all faculties and placed in the second year of the bachelor programme. It consisted of three half-semester sub-courses of which we studied the first two. Student groups formulated their own problems, based on challenges provided by the national railroad operating company including train boarding efficiency and safety on the platform. In the first sub-course student groups studied the flow of crowds on train platforms using actual data. In the second sub-course the students developed computer models of this crowd flow. In the third sub-course the students would develop and possibly test nudges to influence the crowd behaviour. The course involved physics and mathematical modelling, psychology and ethics.

(2) An elective course on Data Science (DS), open to students with relevant pre-knowledge (mostly chosen by students in Data Science and Applied Mathematics bachelor programmes). It consisted of three half semester sub-courses of which we studied the third, in the final year of the bachelor programme. In the first two courses, students were familiarized with mathematical data science methods and with a data science inquiry cycle. In the third sub-course student groups were given a challenge provided by an external academic stakeholder (predicting severe and acute child malnutrition - wasting - in Somalia): “research how to improve existing forecasting model for global acute malnutrition (GAM) and what the societal impact is of such a forecasting model” (assignment document). The course involved the disciplines of data science and ethics.

(3) A compulsory modelling course for first year Applied Mathematics Master students (AMM). Eight groups of students worked for five full consecutive days to create a prototype solution to a problem provided by external stakeholders from regional businesses and industry. The problems were from different domains, in line with the chosen mathematical interests of the students. For example, one problem concerned the assignment of products to locations in distribution warehouses: “optimally assign houses to segments and house types so that as many products as possible fit in their own segment (improve existing model)” (problem description). The week ended with team presentations to the stakeholders. The course only involved the discipline of (applied) mathematics.

The challenges had been formulated by the stakeholders in consultation with the tutors, considering the course duration and the students’ expected pre-knowledge. Student groups still had freedom within the challenges to define their own approach, with most freedom available in PSS and least in AMM.

## Methods

We used a case study approach (Cohen et al., 2007) in which the courses were treated as separate cases. Data collection and analysis took place separately for the separate courses. After an initial within-course analysis, we compared the results across the courses. Participants to the study were student groups in the courses, who came forward after a call for volunteers: two (out of 15) groups in PSS (10 students); two (out of 21) groups in DS (10 students); and four (out of 8) groups in AMM (22 students). We used qualitative methods of data collection as outlined below:

- Documents: Course descriptions, online curriculum resources, selected student products (posters, reports, video's)
- Student group interviews (among others, they drew and explained the resources they had used), individual interviews with tutors and stakeholders.
- Field notes from selected observations of student groups at work during scheduled class time including student presentations and interactions with tutors and stakeholders; during the observations we described in the field notes topics the students discussed (e.g. how to structure the matrices they needed in programming a Markov chain, or the activities the group still had to carry out before the final presentation), and the topics of the interactions between the students and the tutors and stakeholders.

The analysis consisted of a thematic within-case analysis based on the interview data and the student drawings, followed by a cross-case comparison. We used the themes: (a) *professional learning*; (b) *disciplinary learning*; (c) *selection of resources*; and (d) *use of resources*. Several subthemes emerged from the data during the analysis. The documents and field notes enabled us to describe the context of the courses and to interpret the interview data.

## Results

### Students' self-reported learning

The learning reported by the students across the three courses was categorized together with selected examples from the interviews according to themes (a) and (b) and their subthemes (see Table 1). In all three courses student responses could be related to the subthemes, with the exception of modelling techniques (not mentioned in AMM interviews) and communication (not mentioned in PSS interviews).

The learning of particular mathematical concepts and techniques varied per course, group, and student. The tutor sometimes suggested or encouraged student groups to consider particular techniques (e.g., Markov decision processes in AMM). In other cases, students had pre-knowledge of particular concepts (e.g., the concept of Markov chains in a PSS group) and introduced these concepts in their groups, where the concept was then adopted by the group members. In DS this was less the case, as the students all had worked with the same techniques in the related previous courses. However, some DS groups explored and used techniques that were new to them and went beyond what they had learned earlier. In all courses, observations showed that it was not a trivial task to translate the characteristic of the real-world problem into a mathematical model. It took time, and interactions with the tutor (and sometimes the stakeholder) were essential to understand how to

interpret the data and the problem, and how the real-life complexity could be simplified (e.g., in what way the behaviour of a “crowd” differed from that of a “number of individuals”).

**Table 1: Categorizing reported student learning**

<b>Disciplinary knowledge and techniques</b>	
<b>Subtheme</b>	<b>Examples of reported learning</b>
1. Learning to create relations between a real-world situation and the mathematical world.	How to turn a continuous social system into a mathematical description, using physics concepts (PSS); to translate a complicated real-life situation into a model (AMM)
2. Improved programming skills.	Learning to code (in Python) from how other people do it (DS); learning to make the code run faster (PSS; AMM)
3. Particular disciplinary concepts and techniques.	Markov decision processes (AMM; PSS); Simulated annealing algorithm (AMM); methods of data imputation (DS); Maximin principle in ethics (PSS); role of psychology in crowd flow mathematical models (PSS)
4. Working with models on a real-life problem	How approximations can still lead to a good model (PSS); comparing different models regarding their suitability (PSS; DS)
<b>Professional competences</b>	
1. Approaches to problem solving	Asking the right questions about an open problem (AMM); obtaining good results by working in a structured way - using scrum (DS); how errors in the data can take up time in the solution process (PSS)
2. Communication	Preparation and presentation of results (AMM); communication with technical (AMM, DS) and non-technical (DS) stakeholders
3. Collaboration	Effective and efficient decision making as a group (PSS); working with collaboration resources (e.g., Google Drive, Miro) (DS); working under pressure and making it [the project] a success (AMM)
4. Development of identity	Insights into the work of a professional applied mathematician (AMM); Overcoming insecurity about own knowledge (AMM); See how our education can make a real impact (DS); learn what you want to learn [within the challenge] according to own interest (PSS)

During the interviews, several students showed their appreciation for how the course helped to connect their earlier learning. A student in DS remarked:

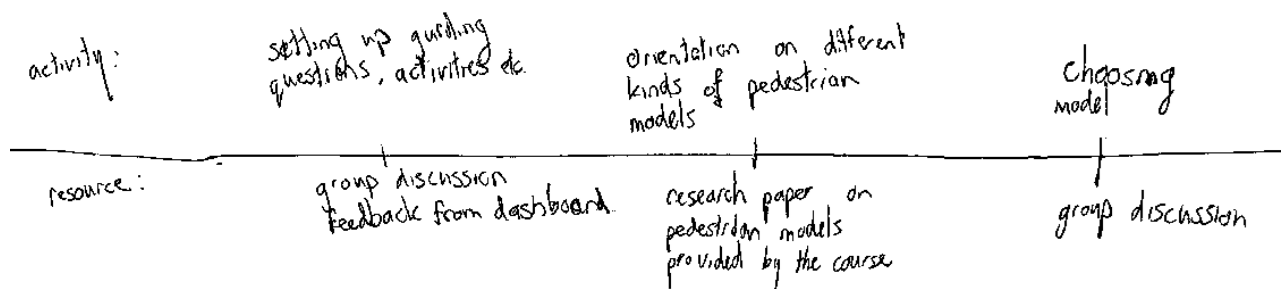
It showed that the other courses, the other things that we've learned so far over the past two years, were actually useful and they are getting us somewhere. And thanks to that, we can actually

explore and pick the methods that we need and actually be able to understand them. So, it's I feel like the data challenges in general, but this one especially kind of brings together all the things that we've learned so far, even if it's a tiny bit of the mathematical concepts.

Other students also valued the connection with real-life problems (“it’s easier to study concrete things”; PSS) and the freedom in CBE (“study something you are interested in”; PSS). There were a few critical comments: students in PSS remarked that CBE took “much more work and time” than traditional courses; other students in PSS would have preferred more input from the lecturers, for example in the form of presentations; a few students in AMM reported that, in their view, they did not learn any new mathematics, and only applied what they already knew.

### Students’ use of resources in relation to their work on the challenge

Different resources became important for student work, depending on the set-up and phase of the course, and the particular challenge. Figure 1 shows part of a drawing by a PSS student, with a timeline indicating the activities and associated resources. The figure shows that in the initial phase (tutor) feedback from the Dashboard (an online curriculum resource designed by two lecturers of the course) was important, next to interactions in the group. For orientation on “kinds of pedestrian models” the students used a curriculum resource (research paper) and during a group discussion, they decided which kind of model they were going to elaborate.



**Figure 1: Schematic representation of a PSS student’s resource system (part)**

In all courses, students reported on the importance of social resources: the stakeholder to initiate and orient the work, the teammates for brainstorming, discussions and collaboration, and the tutors to provide feedback, act as a “sounding board”, and to guide the students’ actions and decisions. Teaching assistants (in DS and PSS) helped the students to organize and plan their work.

In PSS and DS, an online curriculum resource (the Dashboard) was available to allow rapid feedback from the tutors to the students in the initial stages of the project, when the students were formulating their guiding questions, activities and resources. In DS and PSS, the student work was structured by means of a scrum approach; in the much shorter AMM, the tutors had (sometimes twice) daily meetings with the student groups to provide guidance and feedback. Data were provided through the stakeholders (in all courses) who were also available for consultation (daily in AMM, less frequent in DS and PSS). Scientific papers were a resource for the students, in particular in the longer courses (DS and PSS). They were available as curriculum resources (e.g., papers on psychology and ethics in PSS), suggested by tutors, or found by the students themselves. DS students reported consulting the course’s assessment rubric as a guide to their work as they wanted to obtain a high grade.

The mathematical models were implemented using the software selected by the students, which were then used to further explore the challenges. Students had access to software libraries (in DS and PSS) and (in DS) to an initial software model to predict child wasting. One group (in AMM) switched from using the programming language R to Python in order to obtain the desired performance.

The groups distributed the labour and this was one of the reasons that different students used different resources. For example, in PSS, students with previous programming experience focused on programming, while others focused on psychological and ethical aspects of the problem. However, the course organizers fostered students to share knowledge of the different disciplines, for example during regular scrum stand-up meetings (PSS, DS). In PSS, the ethical and psychological issues became a foundation for modelling choices, and hence were also important for the group members focusing on more technical aspects (often the physicists).

The models created by the students became resources for them to solve their problem. For example, in the case of PSS, the model allowed the group to explore and predict the behaviour of people on a train platform in different situation; in the case of AMM to test the behaviour of the model for different configurations of warehouses.

## **Conclusions and discussion**

In conclusion, students in all three courses reported disciplinary learning in mathematics. This learning differed among students and involved learning to deal with the complexity of the real world and its translation into mathematical terms; learning to choose between modelling approaches, learning new concepts and techniques, and improving the skills to implement a model in the form of a computer program. Some students perceived their work as “only applying” their mathematical knowledge. It might be that these students do not see the (non-trivial) operationalization of their knowledge as “learning mathematics”. Such expectations might need to be addressed in course design and further research. The students also reported professional learning, including learning to better solve real-life problems, to communicate, to collaborate and to develop professional identities. Most students appreciated this combination of disciplinary and professional learning as it “brought things together”. They realized that the things they had learned earlier “were actually useful” and “are getting us somewhere”. In that respect the student learning experiences were in line with the aims of CBE (Gallagher & Savage, 2020) and contributed to the students’ disciplinary self-confidence.

The tutors and stakeholders (social resources) appeared essential for the success of the student groups, in line with what was found by Pepin and Kock (2021). As a social resource, we also noted the role of students who introduced new mathematical techniques to their groups. In the longer courses DS and PSS, the data showed the importance of curriculum resources that fostered a structured way of working and providing feedback (using scrum, the Dashboard). These resources helped students to formulate promising questions and problems, and to keep making progress with their tasks. Interactions with stakeholders helped to steer the students in successful directions and increased their sense of working on a meaningful real-life project. DS and PSS had in common that the stakeholder provided data and that an initial model was available for the students. These enabled the students to start exploring relevant questions. The notions of instrumentation and instrumentalization (Trouche, 2004) can be used to describe how students explored the affordances and limitations of resources and



started to use them according to the group's needs. Time for this exploration was, for example, provided in the first PSS course so that sophisticated models could be created in the second course.

The study of the three courses shows that different ways to enact CBE are possible, in which mathematics (in particular mathematical modelling) plays an important role, and in which students can develop competences relevant to their professional life. The courses give rise to learning experiences related to similar themes, but with different emphases. In CBE, student groups have a considerable autonomy to follow their own approach. Still, in order to foster student development and success, the designers of these courses face important decisions, for example on: determining the mathematical domains and competences they want to emphasize, formulating the challenge; creating opportunities for stakeholder interaction; enabling tutor feedback; structuring students' work; facilitating instrumentation and instrumentalization processes; and providing curriculum resources, data, and initial models. The results of our study show examples of how such decisions play out in practice. Future data analysis in this project is aimed at clarifying the connection between the intended curriculum, the enacted curriculum, and the experienced curriculum in the three courses.

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