CEE report of project

Student learning experiences in challenge-based education: the case/s of applied mathematics and physics

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The main aim of this project was to support the mathematics and physics engineering disciplines to provide their education in terms of CBE (see footnote). It was assumed that, whilst considering the TU/e-wide vision statements, one needs to listen to the instructors' and designers' voices (airing their perceptions in terms of affordances and constraints of CBE and its enactment/implementation within the university system), and most importantly, to the students' voices concerning their learning experiences, including benefits and needs, on CBE courses. At the time, we knew that there was experimentation with CBE from teachers in specific courses in mathematics and physics. We wanted to know the experiences of participants, in particular student experiences, in these innovative learning environments. This was done in order to know how we might be able to better support students in these innovative environments. (We call those courses that lean on CBE 'innovative'.)

Hence, in 2021 the study was started to investigate the learning experiences of Applied Mathematics and Applied Physics students in TU/e courses following principles of Challenge-Based Education (CBE) (Pepin, 2021), with the purpose to understand the affordances and constraints of CBE for Applied Mathematics and Applied Physics students and how the students' learning in CBE can successfully be supported. Data has been collected in three courses (for this project) in which students of Applied Mathematics or Applied Physics participated. In the analysis, the courses have been treated as separate cases. See Table for an overview of the courses included in the study.

Table 1. Overview of courses included in the study

Course	Course participants	Remarks on the courses
Modelling week	First year Applied Mathematics Master students	Duration: 1 week.
Data Challenge 3	Mainly Data Science, Applied Mathematics and Computer Science	Third in USE line of three courses, each lasting one quartile.
Sociophysics 1 and 2	Open to students from all bachelor programmes	First and second in USE line of three courses, each lasting one quartile

We asked the following overall **research question** and sub questions:

What are student learning experiences in mathematics and science CBE related courses?

We addressed the three curriculum layers: the intended, the enacted, and the attained/experienced; and we investigated student learning experiences through the lens od 'resources' (see project plan: theoretical lenses).

Sub-questions

(1) On learning objectives:

- RQ1a: What are the learning objectives according to the tutors[1] in the course and how do they relate to the learning objectives and the learning experienced by the students.
- RQ1b: What are the objectives of the stakeholder, and how are they related to RQ1a?

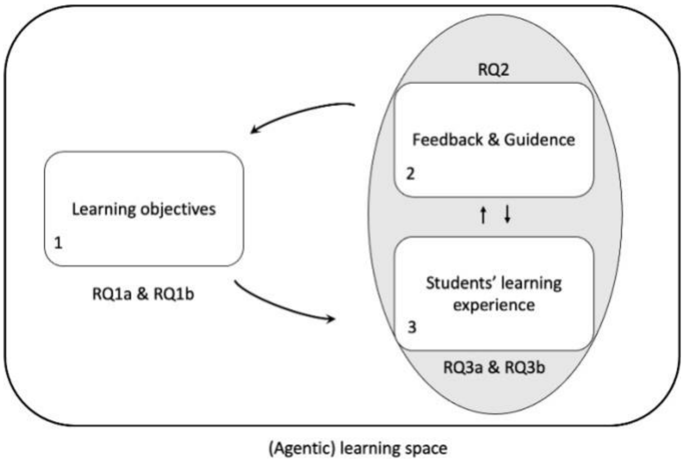
(2) On structure and guidance:

- RQ2: What kind of feedback and guidance did the lecturers, teaching assistants and stakeholders perceive they provided to students?

(3) On students' learning experiences and their perception of resources used:

- RQ3a: How did students perceive the role of the available resources to help them solve their challenge?
- RQ3b: How did students experience their learning in terms of mathematics (Data Science) and professional competences?

Figure 1: Diagram relating objectives to student' learning experience and the interaction with problem owners and tutors



The **data collection strategies** were those described under each of the courses, and they included the following:

- observation (e.g., of student group meetings, student-tutor/teacher meetings, presentations)
- interviews (e.g., with student groups, tutors/teachers, course designers)
- Schematic Representations of Resource Systems (SRRS) of students
- student exit cards
- education documents: TU/e policy document; course documents (e.g., studiewijzer)
- student reports and presentations.

In the following we report on the three courses investigated.

[1] By the term *tutors* we mean course lecturers employed by the university and teaching assistants (TAs, usually students who had already followed the course).

1. **<u>Modelling week</u>** (year 4/first year master)

The Modelling Week (MW) is a course for first year master students that is part of a compulsory course in the Applied Mathematics Master's program. We conducted the study with the aims to:

(1) find out to what extent the course is in line with the Challenge-Based Learning (CBL) approach; where students are expected to develop and apply their knowledge, competencies, and skills by collaborating for the solutions of real-life problems.

(2) To analyze mathematics students' learning experiences by focusing on the resources used.

1.1 Context of the Modelling Week

The Modelling Week is part of a mandatory course (Professional Portfolio) in the Applied Mathematics master program on professional skills development. During one week, first year master`s students work in groups on realistic problems posed by company/research institute representatives (the "problem owners"). The main outcome of this process is students` interpreting and proposing a solution and recommendations for companies via formulating a mathematical model of the given problem and applying mathematical methods in their solutions. Our study has taken place during the Modelling Week of November 2021. Before the modelling week started, two different activities took place. First, a `Kick-off` lecture was given by the course organizers in order to give relevant information regarding the modelling week process and the creation of the student teams related to their interest areas. Eight teams (6-8 students) were created, four of which agreed to voluntarily participate in our research. Next, a team building workshop (`Lego workshop`) was organized with the intention of helping students to get to know their teammates and to learn about team dynamics. Following these events, the Modelling Week started for a period of one week (all day, Monday to Friday). On the first day, problem owners presented the problems for the first time and students were allowed to discuss the details with the problem owners, ask questions for clarification and also request for resources. During the week, students worked as teams to find a feasible and effective solution to the problem. They were guided and supported by university supervisors and problem owners, who also provided feedback on their work. The Modelling Week was concluded on Friday afternoon with the presentations of each team sharing their results. For the majority of students, Modelling Week was the first time they worked on a realistic mathematics problem, posed by an external stakeholder.

For each group we studied, we describe in one sentence the problem they worked on. A more detailed description can be found in the Modelling Week report.

Group 1: optimizing the product arrangement in distribution warehouses.

Group 5: improve a planning algorithm for taxi trips using stochastic boarding times

Group 7: designing a cooling plate that maximizes the cooling capacity, while minimizing the pressure drop between the inlet and outlet.

Group 8: optimizing the rent arrears process for social housing corporations using a personalized approach

1.2 Data collection strategies

The data collection strategies we used during MW are outlined in Table 2 (below). We collected course documents and problem descriptions for the student groups, and we attended the plenary sessions at the start and the end of MW, so that we could understand the context in which the learning took place. Data were collected through non-participant observation of students working together and with their tutors (problem owner, mathematics tutor) during their meetings. These resulted in fieldnotes from these meetings and photos (e.g. of student notes on whiteboards in their meeting rooms). In addition, the following data collection strategies were used (Table 2):

Table 2: Data collection during the MW

General data on MW		
Documents	**Purpose**	
Course documents	Provide context for student learning experience	
Problem descriptions for the student groups	Provide context for the work of the student groups	
Data collected from participants		
Participants	**Instrument**	**Purpose**
Students	Exit Cards, group interviews, drawings	Understand student learning experiences
Tutors (Applied Mathematics)	Interviews	Understand role, expectations and interaction with students
Problem owners	Interviews	Understand role, expectations and interaction with students
Organizers	Interviews	Understand role and expectations
Additional data		
Type of data	**Purpose**	
Field notes during plenary sessions at the start and end of MW	Provide context for student learning experience and the work of the student group	
Student reports	Triangulation with the field notes and interviews	

The exit cards were used to capture how students' attitude, perceived learning and project progress developed during the week, in a way that would take not more than a few minutes of their time. The exit cards were filled out by the students at three different data points (Monday, Wednesday, and Friday), and consisted of five questions to be answered by students (see MW report).

Student group interviews were conducted shortly after MW. During these interviews students drew and explained their resource system (Schematic Representation of Resource system-SRRS; Pepin, et al., 2016). The SRRSs are a schematic representation of how students used and integrated different resources throughout the week to develop a prototype solution to the problem they were given.

1.3 Analysis

In the analysis, we took the main topics of the research questions as categories to organize the data ("sensitizing concepts"). In the process of organizing (coding) the data according to these categories, notions or concepts were developed as properties of the categories. Revisiting the data with the categories and their properties allowed us to see relations between them and help to explain the data theoretically (Walker & Myrick, 2006).

Four categories could be established to analyse the data from the three groups of research questions. Table 2 shows the relationship between each category and each research question.

Table 3. Categories of analysis in relation to each of the research questions.

RQ	Categories	Participants analyzed
1a & 1b	Learning objectives Properties: mathematical and professional.	Organizers, problem owners, tutors, and students.
2	Feedback and guidance Properties: when and what for.	Organizers, problem owners, and tutors.
3a	Kinds of resources reported by students (Pepin & Kock, 2021).	Students.
3b	Student perceptions of their learning experiences (including difficulties experienced). Properties: applying mathematics in the real world and developing social and professional skills.	Students.

1.4 Summary of results

In the following we present the main insights gained regarding each research question, followed by the conclusions.

RQ1: The problem owners took the role of "clients" who provided the real-life mathematical problems for the students to apply their knowledge to. This was in line with the objectives of the organizers and the tutors and the students' experiences. Some students saw the Modelling Week as an outlook on their possible future professional work. Moreover, the organizers, tutors and students described the Modelling Week mainly in terms of as applying mathematics, and only to a limited extent as learning (new) mathematics.

RQ2: The problem owners and tutors attempted to strike a balance between "not letting students get lost" in their projects and "not solving the problem for them." The guidance that the students received from the POs was relevant for the development of the challenges as they received important resources: e.g., the description of the problems, the plans, and the data to work with. Moreover, replies and feedback from the POs helped the groups to keep a focus on prototype solutions that had relevance for practice. For their part, the tutors, with their greater experience, acted as a "sounding board" for the students: students explained their ideas and received feedback. At the same time, the tutors kept an eye on the collaboration in the group, on the progress and on the time frame. Interventions by the tutors, such as the introduction of new mathematical concepts and strategies were generally adopted by the student groups.

RQ3: The students perceived their learning in the first place as gaining experience with the application of knowledge and skills they already had. It is not clear to what extent they considered this as "learning mathematics". Some students reported learning new mathematical concepts and skills, as an extension of what they already knew. The student groups used many resources in their work. Social resources were crucial in the process: the problem owner to orient their work, the teammates for brainstorming, discussions and collaboration, and the tutor as a "sounding board" and to guide the students' action and decisions with careful interventions. The other resources, in particular the software tools, fostered the students' work to the extent in which they helped the students accomplish their goal (a prototype solution to the problem). Multidisciplinary issues sometimes came to the fore, but were not pursued.

Table 4. Resources mentioned by the students

Type of resources	**Specific resources**
Curriculum	Assignment document, problem description, dataset
Social	Tutor, Problem Owner, brainstorming, team discussion, feedback from group members
Cognitive	"prior knowledge", previous experience with integer programming, graph theory, combinatorics, heuristic methods, exact methods, analysis and vector calculus, Navier-Stokes equations, past lecture notes, Markov decision process, probability
General	"Internet", Google, Wikipedia, office software, Google drive, literature (scientific papers)
ICT tools	Python, R, Gurobi, Github, FEM scientific computing, Overleaf, FEniCSx software, ParaView, Linux (and Linux Virtual Machine), unnamed numerical optimization software
Educational technology	Blackboard/whiteboard

For more details of evidence (e.g., student quotes), please refer to the MW report.

The first Research Question (RQ) was related to the objectives of the MW organizers, tutors and POs, and to the students' experiences. These objectives were related to two areas: the application of mathematics, and the development of professional skills. The organizers, considering both students and companies, mentioned both areas; the tutors focused their objectives mostly on the application of mathematics; different students mentioned the different areas, in line with the organizers and tutors. Learning new mathematical concepts and techniques was mentioned by some students. Others saw MW as an orientation on their future professional work. Finally, the POs objectives were directed at finding an answer to a mathematical problem that would help their company or organization. The content of the problems determined the mathematical orientation of the student groups and to some extent also the professional questions at stake.

The second RQ concerned the feedback and guidance the students received from the tutors and POs. The POs guided the students on several occasions during the week; they explained important aspects of the problem, provided data and gave feedback on student suggestions. It was observed that, given the short time available, there was little space to let the students experiment with many difficulties or failures; or to let them follow dead ends for a prolonged period of time. In this sense, slightly adapting the real-life problem so that student groups were more likely to be successful, can also be considered a form of guidance. The tutors were aware that, due to their knowledge and experience, they were important for the student groups to be successful. In addition to asking questions, providing feedback, and challenging the groups to reach greater depths, they also encouraged them to work as a team and prevented them from dispersing. Regular feedback and guidance received by the students appeared to be essential, both regarding the mathematical content and modelling process, and regarding the role of the student groups as "consultants" to the POs.

The third RQ concerns the role of the different resources the students used and the learning they experienced. As indicated in answer to the second RQ, social resources were crucial in the work of the student groups. This applies to the tutor and the problem owner, who guided the students and gave feedback, while giving them enough room to develop ideas on their own. It also applies to the students in the same group, who helped to generate ideas, contributed with their knowledge and skills, and helped organize and distribute the work. Cognitive resources (mathematical knowledge gained in other courses), general resources ("the internet") and software tools were also important for the groups to accomplish their goals. In line with the learning objectives of the organizers and tutors, the students described their learning mainly in terms of the application of knowledge and skills. Even though this application was by no means trivial none of the participants appeared to consider this as a form of "learning mathematics".

Gallagher & Savage (2021) described eight characteristics of CBE, but acknowledge that that there is a variety of ways in which they are visible in different courses and curricula. In MW students worked with open-ended real-world challenges, they collaborated in student groups and with external stakeholders, they were creative to come to innovative solutions, and in all cases the use of technology was crucial. A connection with global themes was not clearly visible in the problems (or at least not made explicit), to a large extent the problems had been defined for the students (instead of the students defining their own problem from a broader challenge) and MW is a monodisciplinary course (although multidisciplinary questions were sometimes raised). This means that MW is in line with most, but not all of the CBE characteristics as defined by Gallagher & Savage. The TU/e has also developed an instrument (the CBL-Compass; Van den Beemt at al., 2022) to evaluate courses. It might help the MW organizers to self-evaluate MW against this instrument.

1.5 Implications for research and practice

Based on our results we provide selected considerations for practice and research.

Considerations for the MW organizers

MW as a form of CBE. As indicated, MW has several characteristics of CBE. The connection with global themes, multi-disciplinarity, and the problem definition by students themselves (from a broader challenge) are less visible in MW. There may be good reasons for this (e.g. the limited time available). On the other hand, there may be possibilities to somewhat extend the scope of MW (e.g. by including the aspect of ethics in problems that use person-oriented data). The MW organizers might want to use the TU/e CBL Compass (Van den Beemt et al., 2022) to get a deeper insight.

Professional and mathematical learning objectives. The MW organizers, the tutors, and to some extent the POs, appear to share a common view on the main mathematical learning objectives (intended learning outcomes) of MW: learning how to create mathematical model on the basis of an open-ended real-life problem and to give a meaningful advice to the problem owner. These objectives largely correspond to the student experiences. Moreover, there are professional learning objectives: communicating, working as a team, behaving professionally. The students mentioned these to a lesser extent. Including a reflection on these objectives and, possibly, including them in assessment criteria might help to make them clearer to the students.

MW as learning mathematics. MW broadens the perspective of Applied Mathematics students by bringing them into contact with real-life open-ended problems and external stakeholders. Students translate the problem in mathematical terms, apply their mathematical knowledge to create a model (some students have to learn new mathematical concepts and techniques for this purpose), and based on using the model, try to give a meaningful advice to the PO. MW fosters the use of higher order thinking skills: the students need to analyze, design/create and evaluate. They learn about some classes of problems to which particular knowledge can be applied and about the possibilities and limitations of doing so in practice. Vergnaud (1998), in his Conceptual Field Theory, made clear that conceptual understanding involves (among others) understanding the situations in which particular concepts can be applied. In this sense, MW is not merely the application of mathematical knowledge by students, but also contributes to their increased mathematical understanding. This is likely to apply even to students who claim that they "have learned nothing new" during MW and seems to be essential learning for students of Applied Mathematics. Here, students might be encouraged to reflect on the mathematical processes they have carried out and how these relate to the characteristics of the real-life problem.

The importance of social resources. In terms of resources, the study once more shows the importance of social and cultural resources (interactions with PO, tutor, group members) in CBE. Earlier studies have also shown this (e.g. Pepin & Kock, 2021). Clearly, a balance must be found between student guidance and freedom, and in the groups that participated in our research, the tutors and POs appeared to be aware of this balance. From the POs this demands an understanding of what can be and what cannot be expected from the student groups. This understanding is fostered if the PO has been a TU/e AM student, or has had a longer relationship with the AM department. Also, the problem formulation requires a balance between the "messiness" of a real-life problem and providing student groups the opportunity to be successful. Some negotiation appears necessary between PO and tutor to accomplish this balance (and mostly took place in the groups we investigated).

Awareness of learning (and teaching) objectives and their alignment. One of the educational aims of the TU/e (and many other universities of technology) is to shift towards a student-centered approach and promote innovative learning environments. In such situations, as Dewey (1938) stated, the curriculum is not a prescription of what learners have to undergo, but that learning must begin with the experiences and interests of the students and is built up by negotiation (e.g., between teacher and students). In our research during MW, we observed that this negotiation must be established between all participants and starting from the learning objectives. On a case by case basis it then becomes possible to identify the disciplinary knowledge students are expected to master and use, as well as the professional competencies and skills they are expected to develop. Thus, this research proposes a procedure to deepen the analysis of this negotiation between teachers and students, as well as the results it produces, which is schematized in Figure 1. The procedure will allow, after establishing the learning objectives, to identify: (1) what kind of guidance and feedback students require to solve their challenges, (2) what are the expected relationships and exchanges among participants, and (3) subsequently determine whether the objectives were achieved.

Relevance of the use and integration of resources in learning. In terms of future research, given the important role of resources when students face real-world problems, it is important to deepen the analysis of their use. The analysis of the use and integration of resources by students in CBE should include the relevant mathematical concepts. This will help to build an understanding of how students build cognitive structures that will enable them to deal with a variety of professional problems and situations related to the type of competencies and skills to be developed. Moreover, it might help course developers to develop curricular resources in accordance with the new pedagogical approach. It is also important to deepen the analysis of the quality of resources: their relevance, practicality, consistency, and effectiveness, for particular projects.

2 <u>Socio-physics 1 and 2</u>

The courses Sociophysics 1 and Sociophysics 2, for second-year bachelor students, are part of the USE Learning Line "Physics of Social System" of three courses. In this USE Learning Line, students develop hands-on experience in combining quantitative approaches (through physics, mathematics, and machine learning-inspired modeling), psychology and ethics, to quantify, model and nudge social systems. The goal is to bring together these different fields in concrete and challenging real-world cases.

We conducted the study with the **aims** to:

(1) find out which characteristics of the CBE approach can be identified in the course (see Van den Beemt et al., 2022);

(2) analyze student learning experiences with a focus on the role of resources in what students learned, and how they learned this.

2.1 Context of Sociophysics 1 &2

The 5 ec courses Sociophysics 1 (SP1) and Sociophysics 2 (SP2) have been part of a TU/e Bachelor college USE-line, together with Sociophysics 3 (SP3). They are facilitated by TU/e innovation Space. In this report the SP1 and SP2 courses are presented together as the analyzed teams worked on the same project in both courses. A short description of each course is given below, based on the information on each course in the OSIRIS catalogue[2] and on the Canvas site.

Sociophysics 1

The objective of SP1 has been described as: *to let students experience how to observe, characterize and measure (quantitatively and qualitatively) a social system*. On the Canvas site, it is added that: *The essence of the course is for student groups to combine quantitative approaches (e.g. mathematics, physics, machine learning) with psychology and ethics.* Stakeholders were invited to provide inspiration for big ideas. In year 2022/2023, period in which the study was carried out, the focus was on: Human Crowd Dynamics (stakeholder: ProRail), Role of social media in financial markets (stakeholder: Duyfken Trading Knowledge B.V.), and Human Augmentation Research and Technology (stakeholder: Student team HART). Each team of 5 students chose the topic they would address during the three courses (SP1, SP2 & SP3).

The course incorporated two core aspects **Challenge Based Education** and **Scrum**. CBE constituted the learning experience and teaching method incorporating complex and real-world problems, whereas Scrum was used as a project management framework where the students, guided by a teaching-assistant, planned, and performed sprints, with activities and deliverables. In the course, the students grouped in teams had to formulate an Essential Question (EQ) they were going to address with their team. They were also asked to formulate Guiding Questions (GQs), Guiding Activities (GAs) and Guiding Resources (GRs) to guide them through the project.

To follow up and support the different teams, different means for interaction and communication with the three lecturers of the course (Physics, Psychology and Ethics) were carried out. Every Monday, by Teams, each team was assigned a ten-minute slot in which they could give progress and ask questions to the lecturers. Also on Mondays, at the end of the meetings with each team, the Physics lecturer met for thirty minutes with all the teaching assistants from the different teams to find out about difficulties in the guidance given to the students. On Thursdays, walk-in sessions were held

[2] https://tue.osiris-student.nl/#/onderwijscatalogus/extern/cursus?taal=en

where each lecturer interacted for an hour and a half with the teams to guide them in their challenges in relation to each subject that the students had to consider: physics, psychology and ethics.

With the aim of helping in the investigation of their challenges, a digital resource was developed for this course: the Dashboard. With this resource, the students were able to communicate with their different tutors regarding the process of identifying and defining the problem. Using the Dashboard, the lecturers (and sometimes the Teaching Assistants) would give written feedback, after which the students could post their revisions.

Sociophysics 2

The objective of SP2 has been described as: *to let students experience how develop models that simulate social systems and provide understanding into how the social system behave.* In this course the different teams continued working towards a solution for their challenge. As stated on the Canvas site: *In the previous course [SP1] you [students] have described the social system, and by now you should have a good idea of what is going on and why. In this course, we go from describing the social system into modelling the social system. In weeks 1 and 2, you will be updating your guiding questions, activities and resources. In weeks 3 to 8, your will be working on your challenge according tot the principles of scrum under supervision of your TA (the scrum master). This means working in weekly sprints and having (daily standups).* Thus, the structure of SP2 was similar to SP1, especially in terms of the use of the CBE approach, the Scrum framework, the meetings with lecturers on Mondays and the walk-in sessions.

2.2 Participants and data collection strategies

Participants in the study were:

- Two groups (out of 15) of 5 students.
- Five tutors (three course lecturers and two teaching assistants)

Table 5 outlines the instruments used to collect data in SP1 and SP2.

Table 5: Data collected in the study

	General data	
Documents	**Purpose**	
Course documents	Provide context for student learning experience	
	Data collected from participants	
Participants	**Instrument**	**Purpose**
Students	Group interviews, drawings	Understand student learning experiences
Tutors	Semi- structured interviews	Understand role, expectations and interaction with students
	Additional data	
Type of data	**Purpose**	
Field notes from selected observations during SP1 & SP2.	Provide context for student learning experience and the work of the student groups in the courses.	
Field notes from selected walk-		

in sessions	
Student products (presentations, posters, reports)	Provide context as well as triangulation with the field notes and interviews.
Students' post and tutors' feedback from the Dashboard	Provide the context for analyzing the role of digital resources for student learning experience.

Student group interviews were conducted shortly after the end of each course. During these interviews students drew and explained their resource system (Schematic Representation of Resource system-SRRS; Pepin, et al., 2016). The SRRSs are a schematic representation of how students used and integrated different resources throughout the week to address their problem. The interviews with tutors were conducted at the end of SP2 course and considered both courses.

2.3 Data analysis

In the analysis, we categorized the data in line with the main topics of the research questions ("sensitizing concepts"). In the process of organizing (coding) the data according to these categories, subcategories were developed. Revisiting the data with the (sub)categories made it possible to see relations between them and helped to explain the data theoretically (Walker & Myrick, 2006).

The two teams analyzed worked on challenges related to Human Crowd Dynamics (stakeholder: ProRail). One of the teams worked on the challenge: *Improve efficiency on the platforms by influencing pedestrians' routing decisions*. The other team's challenge was: *Design methods to optimally (not necessarily homogeneously) distribute passengers on a train platform to improve the boarding time*.

Four categories were established to analyze the data from the research questions.

Table 6. Categories of analysis in relation to each of the research questions.

RQ	Categories and subcategories	Participants
1	Learning objectives	Tutors and students.
	Subcategories: mathematical and professional.	
2	Feedback and guidance	Tutors.
	Subcategories: when and what for.	
3a	Resources reported by the students.	Students.
3b	Student perceptions of their learning experiences	Students.
	Subcategories: applying mathematics in the real world and developing social and professional skills.	

2.4 Summary of results

RQ1: The learning objectives were related to the development of professional skills and competences (e.g., "*Be able to talk to and collaborate with colleagues from different backgrounds*"), and also to a different way of learning disciplinary content, as one lecturer mentioned: "*Solve, using mathematics, problems that are not in books*". In this sense, students were expected, by dealing with real-world problems, not only to develop autonomy but also to gain awareness of the importance of the disciplines of physics, psychology, and ethics for the development of the challenges: e.g., "*what it is to do experiments involving human beings*", or "*try to understand human behaviour and how this behaviour* *relates to the results of models*". These learning objectives were shared by the students themselves, who mentioned their expectation to learn, for example, "*How the laws of physics can be applied to pedestrian systems*".

RQ2: The use of the Dashboard was important both as a means of communication and as a feedback resource. By following the CBE approach in both courses, students were not given a pre-defined question for their challenge. Thus, through the Dashboard, the students received rapid feedback -from each lecturer- on each formulation in quick feedback loops that helped them develop their Guiding Questions, Guiding Activities, and Guiding Resources more quickly, and thus identify the challenge they aimed to solve. The use of the Dashboard also made it possible to efficiently attend to a large number of teams and maintain permanent contact with the lecturers on the development of the challenges. This support was complemented with the guidance given to the students through the Teams meetings every Monday, focused on following the Scrum process and the walk-in sessions (every Thursday) where students could receive specific guidance and feedback related to each of the three disciplines they had to consider: physics, psychology and ethics.

Table 7. Resources mentioned by the students

Type of resources	Specific resources
Curriculum	Stakeholder lectures, onboarding week.
Social and cultural	Group discussions, discussions with lecturers, brainstorming, walk-in sessions, talking with friends (from TU/e), talking with parents (for feedback).
Cognitive	Literature and previous knowledge, Markov matrices, Newton's laws, books about pedestrian modelling.
General	Dashboard feedback, Python, online papers, internet for programming instructions, Teams, Trello, TU/e library, Google scholar, databases, Github, Jupyter notebook, Powerpoint, Matlab, Latex, Overleaf, ChatGPT, Excel. Data set.

RQ3: During the SP1 and SP2 courses, the two observed teams used a variety of resources, which we categorised into four groups. The SRRSs and the interviews allowed us to delve deeper into how these resources were used. It was noted that throughout both courses, discussions between teams, as well as feedback and guidance from tutors, were of particular importance. In this sense, the use of the Dashboard as a resource designed for the course (Digital curriculum resource) allowed the students to move better through the first stage of the development of the projects, where the most important thing is to identify the problem and the questions to be addressed. Finally, we highlight the use and integration of ChatGPT in SP2 as a new resource that we identify as having great potential to become one of the main resources used by students in CBE.

The first research question aimed to find out what the learning objectives of the observed course tutors were and to relate them to the students' expectations of their own learning objectives. In the study, tutors emphasized (1) the importance of students acquiring professional and disciplinary skills and competences, such as learning to interact and work with colleagues from different professional backgrounds, and (2) due to the nature of the problems that students faced, which were real-world problems often involving human beings, it is important that they learn to recognize and integrate different disciplines from other areas of knowledge (psychology and ethics). These learning objectives were related to the expectations of the students, who recognized that the type of challenges they expected to encounter in the course related to the development of models for analyzing pedestrian systems; this involved learning more about the movement of pedestrians.

The second research question was related to the guidance and feedback received by the students during the courses. It was found that an important issue was the creation of a resource system to have continuous communication with students to provide efficient and quick feedback. One resource that stood out was the Dashboard. The communication through the Dashboard played an important role in identifying and defining the problems to be faced by the students. This resource was linked to the content of the other means of communication (e.g., walk-in sessions and Teams meetings). The students considered the Dashboard as an important resource (e.g., "*the dashboard is definitely essential*") and it helped them identify and define their challenge through the quick and effective feedback they received from the tutors.

The third research question concerned the role of the different resources the students used and the learning they experienced. A variety of resources were identified during SP1 and SP2. Among the ones we highlight are the social resources (e.g., group discussions, discussions with lecturers, brainstorming), the use of the Dashboard and the use of ChatGPT as a new resource that students used in SP2. In particular, the interaction with the Dashboard and ChatGPT was analyzed in the context of the instrumental approach and mediation: human actions are shaped by cultural tools (Rabardel & Bourmaud, 2003).

For more details of evidence (e.g., student quotes), please refer to the detailed report of these two courses.

2.5 Considerations for practice and research

Based on our results we give some considerations for the design of courses with a CBE orientation in which mathematical modelling plays an important role, and for further research.

SP1 & SP2 as a form of CBE. The observed courses meet most of the characteristics of the CBE approach identified by Gallagher & Savage (2021). In particular, being a course with students from various disciplines, it was observed how different profiles worked together for the solution of challenges.

Learning objectives and expectations. The tutors shared a common vision of the learning objectives in professional terms: students should learn to be autonomous and to work collaboratively. But also, each lecturer emphasized the role of their discipline as an element that students must recognize beyond the profile of each student. Thus, given the nature of the challenges, students must become aware of psychological and ethical issues and their role in the development of physical-mathematical models.

SP1 & SP2 as learning mathematics and physics. In our study of this USE Learning Line “Physics of Social System”, we were able to observe how the activity carried out by the students corresponds to learning how to mathematize the reality. To do this, they had to learn to formulate guiding questions and to define the challenge they wanted to address. Given the nature of the challenges themselves, the development of the challenges corresponded to mathematical modelling problems. In this sense, mathematics and physics need to be approached in a way that is in line with CBE, in the context of the acquisition and development of knowledge, competencies, and skills (professional and mathematical) and the use of different resources which mediate the students' and tutors' activity.

Relevance of the use and integration of resources in learning. Our study highlights the fact that the development of professional and disciplinary skills and competences is closely related to the way students integrate and use a variety of resources to address their challenges. In this sense, during the development of challenges, students may incorporate new resources, which in turn must first recognize their characteristics and how they can help them in solving their projects. In our study, one of the new resources that students incorporated was the use of ChatGPT. We consider this case a positive example of how ChatGPT can contribute to education, but further research is needed to analyze the impact that this resource will have in the students learning.

3 Data Challenge 3

This document reports on student learning experiences in the TU/e course Data Challenge 3 (DC3). DC3 is a course for third year bachelor students and is part of a USE line consisting of three Data Challenge courses (1, 2 and 3). Main participants in this USE line are students of Data Science, Applied Mathematics and Computer Science. We conducted the study with the aims to: (1) find out which characteristics of the CBE approach can be identified in the course (see Van den Beemt et al., 2022); (2) analyze student learning experiences with a focus on the role of resources in what students learned, and how they learned this.

3.1 Context of the study: Data Challenge 3.

The 5 ec course Data Challenge 3 (DCH3) has been part of a TU/e Bachelor college USE-line, together with Data Challenge 1 (DCH1) and Data Challenge 2 (DCH2). Data Challenge 1, 2 and 3 have been scheduled in the first, second and third year of the Bachelor programme respectively. During DCH1 and 2, the students followed a way of working similar to DCH3 (e.g. working with real or semi-real data, following a scrum approach), but the assignments were less open than in DCH3 (e.g. in DCH1 & 2 the particular mathematics techniques had been prescribed). The objective of DCH3 has been described in the OSIRIS course catalogue[3] as: *to teach students how to perform large-scale data-driven analyses themselves, combining the technical skills acquired earlier in the Data Science program with insights gained in methodological courses. Data Challenge 3 is the final course in this series and shall familiarize students with the skills of designing and executing a data analysis on a complex data source with time-related data from multiple angles for a public stakeholder (governance or society). The focus is on exploring complex, unknown data sources, developing analysis hypothesis with stakeholders, conduct the analysis, and visualizing and communicating complex analyses in an understandable way to a public stakeholder, and reflecting on the choices and their impact on the stakeholder.*

The more detailed learning objectives (see detailed report on this course) specify that learning to "handle and resolve uncertainty", as it occurs in the practice of a professional Data Scientist, is also an important aspect of the course.

During the course, self-selected groups of 6-5 students worked on the problem they had derived from the more general challenge. The course used a scrum approach in which the groups, guided by a teaching-assistant, planned and performed sprints, with activities and deliverables. A few plenary

[3] https://tue.osiris-student.nl/#/onderwijscatalogus/extern/cursus?taal=en

meetings had been planned, but most contact between the course lecturers, the stakeholder and the groups took place through walk-in sessions, for which students could book a time slot.

The external stakeholder was the Zero Hunger Lab (ZHL), a research group of Tilburg University that aims to "use data science to contribute to realizing global food security" (Tilburg University, 2023). ZHL has developed a forecasting model to predict cases of child wasting (an immediate, visible, and life-threatening form of malnutrition) in different regions in Somalia.

The student groups in DCH3 were given the assignment "to research how to improve the existing forecasting model for global acute malnutrition and what the societal impact is of such a forecasting model" (Eindhoven University of Technology, 2022). Groups could choose to focus on the (quality of) the data, on the model itself, or on a combination of both and were asked to approach the assignment from a technical, a stakeholder, and an ethical perspective. For each perspective the assignment document specified student products.

The Canvas site contained links to resources for the students: documents with background information; data and a baseline model a starting point for the technical work of the student groups; background literature, among others for the ethical aspects considered in the course. Literature was accessible in Perusall[4], an online environment allowing students to make notes and ask questions on the literature. Among others, Perusall contained documents with an explanation on the setup of the course and advice on how to succeed. Another resource was the "CBL Dashboard", a digital tool developed for the Sociophysics USE learning line. In the tool, the groups could write down their guiding questions, guiding activities and guiding resources, and receive feedback from the lecturers. Use of the dashboard was not obligatory.

This study of DCH3 has taken place during the first quartile of the 2022-2023 academic year.

3.2 Participants and data collection strategies

Participants in the study were:

- Two groups (out of 21) of 5 students.
- Five tutors (three course lecturers and two teaching assistants)
- One external stakeholder (ZHL)

Table 8 outlines the instruments used to collect data in DCH3.

Table 8: Data collected

	General data	
Documents	**Purpose**	
Course documents	Provide context for student learning experience	
	Data collected from participants	
Participants	**Instrument**	**Purpose**
Students	Group interviews, drawings	Understand student learning experiences
Tutors	Semi- structured interviews	Understand role, expectations and

[4] www.perusall.com

		interaction with students
Stakeholder	Semi- structured interviews	Understand role, expectations and interaction with students

	Additional data
Type of data	**Purpose**
Field notes from selected observations during DCH1.	Provide context for student learning experience and the work of the student group in DCH3.
Field notes from selected walk-in sessions	
Student products (posters, papers and videos; the model itself was not collected)	Provide context as well as triangulation with the field notes and interviews

Student group interviews were conducted shortly after the end of the course. During these interviews students drew and explained their resource system (Schematic Representation of Resource system-SRRS; Pepin, et al., 2016). The SRRSs are a schematic representation of how students used and integrated different resources throughout the week to address their problem.

3.3 Data analysis

In the analysis, we categorized the data in line with the main topics of the research questions ("sensitizing concepts"). In the process of organizing (coding) the data according to these categories, subcategories were developed. Revisiting the data with the (sub)categories made it possible to see relations between them and helped to explain the data theoretically (Walker & Myrick, 2006).

Four categories were established to analyze the data from the research questions. Table 9 shows the relationship between the categories and the research questions.

Table 9. Categories of analysis in relation to each of the research questions.

RQ	Categories and subcategories	Participants
1a & 1b	Learning objectives Subcategories: mathematical and professional.	Tutors, stakeholder, and students.
2	Feedback and guidance Subcategories: when and what for.	Tutors and stakeholder
3a	Resources reported by the students.	Students.
3b	Student perceptions of their learning experiences Subcategories: applying mathematics in the real world and developing social and professional skills.	Students.

3.4 Summary of main results

RQ1: The learning objectives mentioned during the interviews concerned the development of disciplinary and professional of competences. In terms of disciplinary competences, the application of methodologies, tools and concepts learned earlier was considered important, including how to deal with them in a “messy” realistic situation. Moreover, it was expected that students would develop the ability to substantiate decisions with a disciplinary rationale and showing ethical awareness. Finally, it was considered important that students learned to present their results in such a way that stakeholders could understand them (e.g. using visualization tools). Professionally, learning objectives were directed to teamwork, defining and (re-)scoping a problem, working under more or less realistic conditions (of complexity, uncertainty and lime limits) and collaborating with a stakeholder. One lecturer summarized the aim of the course as: “*test student ability to be a data scientist; mature in the data science techniques, in learning and in working as a team*”; IntLct1.

The student expectations regarding disciplinary and professional learning overlapped with the learning aims of the tutors. Some students had additional aims for themselves, such as: developing programming skills and learning to be a scrum master. The students also had expectations regarding the collaboration with their peers: “*we want to work with people who have a similar working style to ourselves and also we will kind of like have the same expectations in terms of the grade and how much we would like to put in like the effort and also what we would like to get out of the course*” (ST2). The potential impact of their work (i.e. results that would be used in practice) was mentioned by some students and is considered one of the motivating aspects of CBE.

The stakeholder was mostly interested in new research directions for ZHL and hoped to get inspired by student ideas. His expectations were considered in the preparation of the course documents, but he was not involved in the preparation of these documents, and the formulation of the challenge took a somewhat broader perspective than that of ZHL: *While ZHL gave you the assignment, the impact of your work reaches beyond ZHL. Understanding who has an interest in the outcomes of your assignment and who is impacted, i.e., who is a stakeholder, is central to both the technical analysis and the societal ethical reflection*; JBG060 Data Challenge 3 2022/2023.

RQ2: The preparation phase of the course was crucial for successful student guidance. The scope definition of the challenge and the assignment document set boundaries for the activities of the student groups. The initial model gave the students a chance to address the challenge in a meaningful way within the time frame of the course. Moreover, creating the tools and documents prepared the TAs for their role during the course. During the course, a system was in place to guide the student groups and give them feedback. A basic structure was provided by the four scrum sprints. The main role of the TAs was to provide the groups with feedback on their work processes, so that they made progress and collaborated in a productive way. The TAs received guidance during the weekly meetings with a lecturer, while at the same time important issues were brought to the attention of the lecturers. In this way a limited number of lecturers could enact the Challenge-Based course with relatively sophisticated (mathematical) content for a group of approximately 100 students. The TAs also gave the students feedback on the Data Science content of the course, but for more complicated questions they referred them to the walk-in sessions with the lecturers. The walk-in sessions enabled direct contact between the student groups and the lecturers as well as the stakeholder. This gave them the expert feedback they needed to choose the right direction for their Data Science work with the model and the data. An important part of the feedback was concerned with managing the student expectations and reassuring them regarding the uncertainty they encountered. The lecturers’ experience in enacting this course had given them insights into potential student problems and the ability to anticipate them. The online feedback tool (Dashboard) had been used in a limited way. This may be due to the fact that it had not yet been fully integrated into the course's structure that had been developed over several years.

RQ3: The students used a variety of resources, partly depending on the phase of the project they were in (see Table 8 and Figure 2). In all phases the course structure (e.g. using scrum sprints) and the tutor and stakeholder feedback helped them stay on track. The needs of the stakeholder, communicated during an initial presentation and stakeholder sessions, were a guiding factor in the work. Students helped each other during brainstorms sessions and while they collaborated in subgroups on different tasks (e.g. the ethics, the data, or the model). Knowledge gained in earlier (data challenge) courses was used by the students to work on the challenge, and also to explore new techniques. Students experienced that, in contrast with previous courses, numerical results were not the most important, but the ability to explain why a particular approach did or did not work.

Table 10. Resources mentioned by the students

Type of resources	**Specific resources**
Curriculum	Information on Canvas, documents / information on Perusall, data and baseline model, weekly ethics readings (papers), Miro board, Dashboard (online feedback tool)
Social and cultural	(discussions with) Group (members), tutor, teachers (technical feedback meeting; ethical discussion meeting), asking stakeholders for their needs
Cognitive	From past courses (e.g. previous Data Challenge courses): preprocessing techniques, insight into the tools and models that could be used; information from students' own summaries of previous courses.
General	*Online resources and websites:* medium.com, scientific papers found online, blogs (regarding ethics), TU/e library, websites on how to write code, collaboration tools (Canva), Google Colab, Google drive, Canva.com (for visualization), google docs visualization libraries, Ministry of finance in Somalia, Food Security and Nutrition Analysis Unit – Somalia (FSNAU; e.g. additional datasets). *Software:* Excel, Python, Jupyter notebook, programming libraries, Final Cut pro (video production)

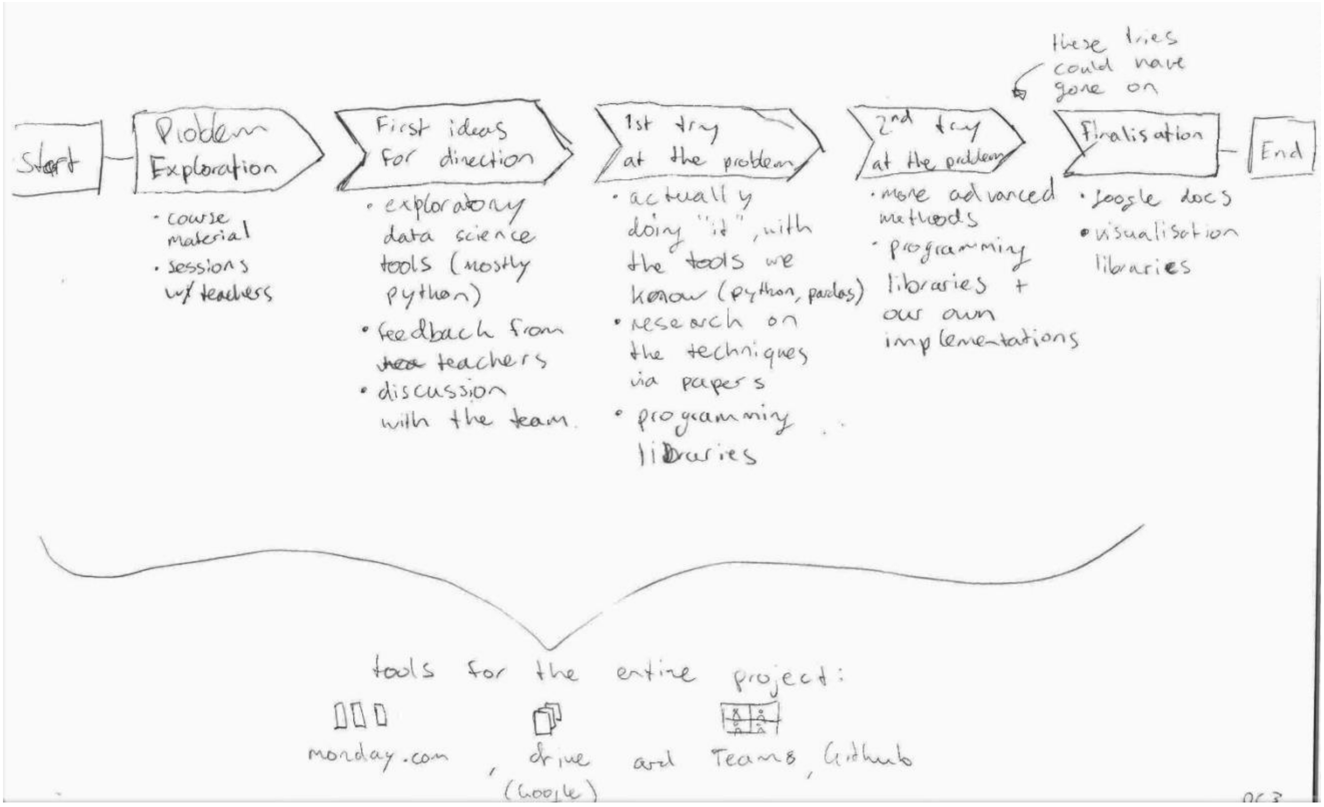


Figure 2. St5's drawing of resource system

Research question RQ1a concerned the learning objectives of DCH3 in relation to the students' reported learning. Research question RQ1b concerned the stakeholder's objectives. The learning objectives were related to (a) disciplinary competences, and (b) professional skills. In terms of disciplinary competences, the learning objectives focused on the application of earlier acquired methodologies, tools and concepts in a "messy" realistic situation, on the ability to substantiate decisions ethically and with a disciplinary rationale, and on clear visual presentations of results. Some groups used more sophisticated technologies than what they had earlier learned. Professionally, the learning objectives focused on teamwork, problem definition, working under realistic conditions, and collaborating with a stakeholder. The student expectations were in line with the learning aims of the tutors, while some students had additional disciplinary or professional aims for themselves. The stakeholder hoped to get new ideas from the work of the student groups and was less interested in thee numerical details. The student assignment took a somewhat broader perspective than that of the stakeholder.

RQ2 concerned the feedback and guidance the students received during the course. In the preparation phase of the course crucial resources were created or made available to guide the students, such as the assignment document, data, the base model and reading material on ethics. TAs were prepared by contributing to these and other resources. During the course, systematic student guidance and feedback were foreseen: four scrum sprints, an online feedback tool (dashboard; used to a limited extent), feedback during technical, ethical and stakeholder sessions (walk-in sessions) and interactions with the TA. TAs received guidance themselves and brought important information to the attention of the lecturers. An important part of the feedback consisted of student expectation management and helping them deal with the uncertainty they encountered. The lecturers' experience in enacting this course had given them insights into potential student problems and the ability to anticipate them.

RQ3 concerned the role of the different resources the students used and the learning they experienced. Social resources (tutors and the stakeholder) were crucial in the work of the student groups. Students in the same group were also resources for the other group members, as students brainstormed together, contributed with their knowledge and skills, and helped organize and distribute the work. Curriculum resources, cognitive resources (mathematical knowledge gained in other courses), general resources (google; applications for teamwork) and software tools were also important for the groups to accomplish their goals. In contrast to other CBE courses (see e.g. Salinas-Hernández et al., 2022) the students had, to a large extent, access to the same cognitive resources as they had all followed DCH1 and DCH2, in which they had become acquainted with various data science techniques.

Figure 2 shows the eight general characteristics of CBE identified by Gallagher & Savage (2021). Almost all of these were present in DCH3: the students defined their own approach in the context of an open challenge connected to a theme of global importance; they collaborated in student groups and with an external stakeholder; their creativity to come to innovative solutions was of interest for the stakeholder, and the use of technology was crucial. The course is to a limited extent multidisciplinary, with participation of students from data science and applied mathematics mostly. For the participating students, the course demanded a deep understanding, acquisition and application partly facilitated by the content of DCH1 and DCH2. This went hand in hand with the development of professional skills and allowed room for some students to pursue their own learning goals.

For more details of evidence (e.g., student quotes), please refer to the detailed report of this course.

3.5 Implications for research and practice

Based on our results we give some considerations for the design of courses with a CBE orientation in which mathematical modelling plays an important role, and for further research.

DCH3 as a form of CBE. As indicated, DCH3 has most of the characteristics of CBE identified by Gallagher & Savage (2021), with perhaps multi-disciplinarity being somewhat less visible. In their TU/e CBL compass, Van den Beemt et al. (2022) distinguish 12 dimensions and a total of 35 subdimensions that can be present to a greater or lesser extent in CBE. To get a deeper and more detailed insight into the "CBE profile" of DCH3 organizers might want to consult this compass.

Learning objectives and expectations. The lecturers, TA's, and stakeholder appeared to share a common view on the main student learning objectives of DCH3: with limited guidance collaboratively using data challenge technology to create prototype solutions for an open-ended real-life challenge connected to a relevant issue in society and providing a well-founded advice to the stakeholder; while dealing with the associated complexity, uncertainty and boundary conditions. These objectives, which formed an integration of professional and disciplinary objectives were much in line with the student experiences. The students who participated in the study appreciated the opportunity to pursue some of their own objectives, which is in line with the importance of student ownership in CBE (Van den Beemt et al., 2022). In this respect, DCH3 shows constructive alignment between objectives and enactment, which could provide valuable insights to designers and organizers of other CBE courses involving mathematical modelling.

The stakeholder indicated limited involvement (possibly due to the time frame of the course preparation) in the challenge formulation and the creation of the base model. Therefore, he said, he was less familiar with some aspects of the course, such as the role of ethics, some student questions on the model, and the perspective on multiple stakeholders that was asked from the students. The course organizers could consider giving even more feedback to the stakeholder on his position and role within the course.

DCH3 as learning mathematics. DCH3 is the third in a learning line of three data challenge courses and the only one with an explicit CBE orientation. During the first two, students became familiar with data science techniques, a data science modelling cycle and a way of working (scrum). They worked with (partly) realistic data, but without an external stakeholder and with less open assignments than in DCH3. As a result, the students who started DCH3 had become familiar with the mathematical tools they were going to need, and, building on this basis, were able to learn new tools in a relatively short period of time. In line with other CBE oriented modelling courses (e.g. Modelling Week for first year Applied Mathematics master students), DCH3 broadened the disciplinary perspective of the students by bringing them into contact with real-life open-ended problems and external stakeholders, thus creating a first experience of the work of a professional data scientist. Dealing with uncertainty and complexity are key aspects of this work.

Preparatory courses in which students learn the necessary mathematical techniques (DCH1 and DCH2) and then using these techniques (and more) in a CBE course (DCH3) is a particular way of implementing CBE. A question surrounding CBE with a mathematics focus is to what extent also the basic techniques can be acquired through CBE. This question has not been answered yet and is an issue for further research. Another question is how the learning outcomes of the students vary, in the light of the distribution of tasks in the student teams.

The importance of social resources. Earlier studies (e.g. Pepin & Kock, 2021) have pointed out the importance of social and cultural resources (interactions with stakeholder, tutors, group members) to guide student work in CBE. In DCH3 a structure has been put in place for this purpose: course preparation for the TAs, course planning, using scrum, the online dashboard (used only to a limited extent), student meetings with the TA, walk-in session with lecturers and stakeholders, meetings between TAs and a lecturer, etcetera. Such a structure appears crucial for the success of large courses such as DCH3 (with approx. 100 students). A suitable structure depends on the course requirements, but the importance of a structure to guide the students should be taken into account by course designers.

Relevance of the use and integration of resources in learning. This study once more shows the importance of carefully designed curriculum resources as a precondition for the success of student work in CBE. Regarding DCH3 we mention the assignment document, the base model constructed by the TAs, the data used to run the model, background material on the work of ZHL, papers to introduce the ethics part of the course. According to the student drawings and interviews, the curriculum resources were an important guide for the students, in particular in the initial stages of the project. Apart from these, the students looked for general resources, such as reference information, software tools, scientific papers and websites that support collaborative work. Future research might focus in more detail us on those characteristic of curriculum (and other) resources that make them successfully support students in mathematically oriented CBE courses, as well as on the alignment and consistency between resources.

4 Overall insights

- Students of the three courses studied regarded their learning experiences as an outlook on their future professional work: "working like a real engineer".
- Special attention and considerations should be paid to the provision, use and integration of "resources" (curriculum resources (e.g., textbooks, teacher curricular guidelines, worksheets), social and cultural resources (e.g., conversations with tutors, peers and friends), cognitive resources (e.g., concepts and techniques), and general resources (e.g., software, internet, and other digital resources), and their quality. Of particular importance were the social resources, and the acknowledgement of new resources (e.g., CHATGPT). Regular and quick feedback

on students' work was also seen as essential, for example, with digital resources (e.g., Dashboard) in larger courses.

- The alignment of expectations between students, tutors/teachers and problem owners was regarded as important.
- Most students saw the "application of knowledge and skills", not "new" mathematics or physics knowledge, but the "extension of knowledge" (in mathematics and physics) as important aspects of what they learnt in the CBE courses. However, within the groups students also taught each other (as they mostly worked in interdisciplinary groups) and in those environments they learnt/adopted new mathematical concepts and strategies. In terms of mathematical knowledge, the main aspect students learnt was related to mathematical modelling, a higher order thinking skill that permeates the sciences.
- In terms of student 'preparation' for CBE courses, we claim that serious consideration should be given to the preparation of students for CBE, like we saw in selected courses, so that students feel the benefit early on (and do not feel lost). In such a way, students' interests and negotiation (between student and teacher) of project (content) can be discussed.

5 Limitations of the research

One limitation of the study is that we relied on self-reported information from the students, that was only accompanied by selected observations of walk-in sessions. However, we note that these observations were in line with the student learning experiences according to the interviews.

Concerning the different courses:

- Modelling week: One limitation of the study was that we did not collect data on the details of the mathematical modeling process itself. Our observations and other data only provided a general idea of this process. A future study could shed more light on the relationship between the modelling process, the use of resources, and student learning. This point is of relevance given the importance of modeling in mathematical practice, especially when students engage in mathematical modeling activities with data-rich modeling tasks (e.g., Stillman & Brown, 2021). Therefore, one aspect to delve into is what the meaning production processes are when students engage in a data-rich modeling situation; another, what is their perception and awareness of that process. For example, about the difference of focusing on the concepts and knowledge related to the situation (phenomenon), of which the data set is a particular example of that phenomenon; or focusing on modeling a particular data set without considering in its entirety the key features of the phenomenon.

- Sociophysics 1 & 2: One limitation of our study was the time of observations and data collection for this course as compared to the other two: the time we spent on the data collection of this course was distributed over a longer period of time, compared to the other two. We hypothesize that we could develop potentially more insights into the running of the course. This could lead to a bias, or insights that we did not develop from the other two courses.

- Data Challenge 3: One limitation of the study was that in this there were two groups of students who participated in the study – these were asked to do so by one of the lecturers. Both groups displayed a high motivation to be successful and strived for a high grade in the course. In that respect they may not be fully representative for the whole DCH3 study group and it is possible that we have described a "best case scenario". For future studies it may be advisable to also collect quantitative information from the whole group. A second limitation of this course was that our study only involved

DCH3, with a few observations added from DCH1. What we can say about the cohesion between the three courses is limited to what participants said during the interviews.

6 Additional comments

During the two years of the project, not all 3 postdocs worked all the time: it started with Ayse Kilic and Zeger-jan Kock, until Zeger-jan had to stop for 6 months (because of contractual obligations) and Ayse resigned as postdoc (and started a new post in quality assurance at TU/e). Ulises then took over starting work with TU/e in 2022.

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