Learning gains in traditional versus challenge-based higher engineering education

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ABSTRACT

Engineering education at Eindhoven University of Technology (TU/e) is in the process of changing from instruction and teacher-based education to inquiry- and challenge-based education, where students are challenged to solve open-ended problems in collaboration with stakeholders in the field of science and technology (Eindhoven University of Technology, 2018) and hence the teacher's role becomes that of a coach. To determine students' learning gains in both traditional and innovative education (i.e., challenge-based learning) at TU/e, we asked the following research question: *Which (kinds of) learning gains do engineering students perceive in challenge-based learning versus traditional learning?* To answer this question, we interviewed 13 students from "science" studies (e.g., Applied Mathematics), "core engineering" studies (e.g., Mechanical Engineering), and "social engineering" studies (e.g., Sustainable Innovation) about their perceived learning gains in traditional as compared to challenge-based courses. We used a new tool "pie chart drawing" to elicit students' self-reported learning gains. Furthermore, we investigated students' reflections on the learning trajectory "Responsible innovation in a global context" to get deeper insights into learning gains in a challenge-based learning trajectory. The results showed that students perceived learning gains regarding their disciplinary conceptual and procedural knowledge; general cognitive learning; affect and thoughts related to learning; skills on teamwork and communication; and knowledge and skills about enterprise and business. Learning gains that were mostly obtained in traditional courses focused on disciplinary conceptual and procedural knowledge. Learning gains in challenge-based courses stimulated students' teamwork skills and collaboration with outside stakeholders (e.g., companies; institutes). General cognitive learning, communication with other students, and affect and thoughts related to learning were acquired in both traditional and challenge-based courses. The implications for CDIO related principles and engineering education in general will be discussed.

KEYWORDS

Innovative engineering education, Learning gains, Challenge-based learning, Standards: 2, 3, 4, 5, 7, 8.

INTRODUCTION

At Eindhoven University of Technology (TU/e) in the Netherlands, engineering education has been developing from instruction and teacher-based education into inquiry- and design-based learning in which students investigate and develop products as a solution to technical problems.

In its strategy for 2030, TU/e further specifies the main educational approach as “challenge-based learning” (CBL) (Eindhoven University of Technology, 2018). Currently, there are pilots to develop CBL at TU/e.

The definition of CBL varies between different studies. In a study by O’Mahony et al. (2012), a challenge is, for example, formulated as a relatively closed problem. Other literature states that CBL refers to open-ended and authentic situations (e.g., Membrillo-Hernández et al., 2019; Rosén et al., 2018). An authentic problem is also part of design-based learning (DBL), which has already been implemented at TU/e. DBL consists of open-ended and authentic scenarios which students use to develop a product in multidisciplinary teams (Gomez, 2014). The difference with CBL is that students in CBL collaborate with industry, companies and organizations (Eindhoven University of Technology, 2018) when working on open-ended and authentic problems. This is in line with literature that shows higher learning gains when challenges are formulated in collaboration with industry as compared to school-based challenges (Membrillo-Hernández et al., 2019).

Promising learning gains are claimed in literature regarding CBL (e.g., O’Mahony et al., 2012; Martin et al., 2007). O’Mahony et al. (2012) found more interactions about knowledge in their challenge-based than in their lecture-based course. In addition, participants of the challenge-based course had a better understanding of synthesis of concepts. In the study of Martin et al. (2007), students of a challenge- and inquiry-based course, and of a traditional course both gained knowledge about bio transport, but the students in the challenge and inquiry-based course gained more innovation skills. Moreover, when asked to rate how much they preferred challenge-driven education over traditional education, almost all students in the study of Rosén et al. (2018) provided high ratings for the project-based CBL setting.

At TU/e, students’ learning outcomes are measured in both the instruction-based and challenge-based courses, but their gains in learning are often unclear. To measure students’ learning gains at university, Vermunt et al. developed a general learning gains framework (Vermunt, Ilie & Vignoles, 2018). However, a learning gains framework specifically for engineering education was still lacking. Therefore, we decided to develop such a framework in a previous study (Van Uum & Pepin, 2019). Our framework is based on the CDIO framework for engineering education combined with the general learning gains framework of Vermunt et al. (2018) and inspired by a framework for mathematical proficiency (National Research Council, 2002). The developed framework consists of five categories: the disciplinary conceptual and procedural knowledge strand (e.g., understanding engineering concepts and procedures); the general cognitive learning strand (e.g., critical thinking, system thinking, and problem solving); the affect, thought and learning strand (e.g., ethics and responsibilities of an engineer); the teamwork and communication strand (e.g., written and oral communication); and the entrepreneurial learning strand (e.g., enterprise and business context).

The learning gains framework for engineering education has been validated via interviews with students at TU/e. During these interviews, we became aware of possible differences between students’ perceived learning gains in CBL and in traditional teacher-based courses. Therefore, in the current study, we used our learning gains framework for engineering education to analyze students’ learning gains in both types of education. The research question of this study is: *Which (kinds of) learning gains do engineering students perceive in challenge-based learning versus traditional learning?*

METHOD

Participants

To investigate students' learning gains in CBL and traditional learning, we interviewed 13 students of TU/e, of which five were men and eight women. Eleven students followed a second year Bachelor's degree program and two students were further along with their studies. Nine students participated in the CBL learning trajectory "Responsible innovation in a global context". At a final event of this learning trajectory, at which the students presented their projects during an information market, 12 students were asked to participate in our study. Of these 12 students, nine were willing and available to be interviewed. As we wanted more input from "core engineering" students, we decided to approach students from a second CBL learning trajectory "Engineering Design". Four additional students were willing to participate in our study. The 13 interviewed students consisted of four students from Sustainable Innovation and three students from Industrial Design. In the remainder of this paper, we will refer to these studies as "social engineering" studies. Applied Mathematics was studied by three students. We will refer to this as "science" studies. Finally, the term "core engineering" was used for the studies Mechanical Engineering (two students) and Computer Science and Engineering (one student).

In addition to the interviews with students, we analyzed reflections that were written by eight out of the nine participants who had followed the challenge-based learning trajectory "Responsible innovation in a global context".

Instruments

To access students' perceived learning gains, we used semi-structured interviews. In each interview, students were asked to describe their perceived learning gains at the university, in which courses they had acquired these learning gains (to determine whether the learning gains were acquired in traditional or challenge-based courses), and why these learning gains were important to them. After students had mentioned all their perceived learning gains, they were asked to visualize the size of their learning gains via the strategy "pie chart drawing". For that, they divided a circle into different parts, with each part representing a particular learning gain. In addition, they wrote a short explanation about each learning gain, and in which courses they perceived the learning gains. This provided us with an overview of students' learning gains that we could connect to their explanations in the interviews.

To determine students' perceptions of the challenge-based learning trajectory "Responsible innovation in a global context", they were asked to write (at least) one page of reflections on perceived learning gains in this learning trajectory.

Procedure

Students who had worked on the same project were interviewed together when possible. Due to different schedules, three students were interviewed alone and ten students were interviewed in pairs. The interviews were recorded on a voice-recorder and transcribed by a student assistant.

To acquire more information about students' learning gains during challenge-based learning, the learning trajectory "Responsible innovation in a global context" was investigated. The overall goals of this learning trajectory were: to understand the relevance of responsible innovation in a global context and how these innovations work in practice, to analyze and design responsible innovations, to reflect on analyses and designs, and to communicate ideas about responsible innovation in a global context to stakeholders (source: Osiris, TU/e). To reach these goals, students worked together in multidisciplinary/transdisciplinary groups on real-life projects supervised by engineers from companies/industry and the course teacher. In the first quartile, students learned about the context of responsible innovations. In the second quartile, they started to make design decisions to develop a product. In the third quartile, they thought about how to implement the product and how the product could have an impact. At the end of the learning trajectory “Responsible innovation in a global context”, students were asked to write down their perceived learning gains. The learning gains of eight students (who were interviewed as well in the first part of our study) were analyzed.

Data analyses

For each learning gain that students mentioned in the interview, they explained in which course or courses they had acquired this learning gain. Via the course descriptions and information that the students provided on these courses, we determined whether the course was a “traditional” or “challenge-based” course. Although our definition of challenge-based learning, provided in the introduction section of this paper, includes interaction with clients from industry, we decided to include results on design-based learning as well, as these courses were clearly different from instruction-based education. During design-based learning, students at TU/e worked together and designed a product as a solution to a problem that could be formulated by the teacher or the students without contact with clients from industry.

The “pie chart drawings” of the students were analyzed using the Grounded Theory approach of Glaser and Strauss (1967). First, we grouped similar learning gains together and labeled these with the same category name. For example, learning gains as “basic knowledge”, “theoretical knowledge” and “pure theory” were grouped under the category “theoretical knowledge”. Subsequently, for each category, we differentiated between “traditional” and “challenge-based” learning gains depending on the courses that student mentioned when referring to their learning gains. Each category was connected to one of the “strands” of our learning gains framework for engineering education. In the results section, for each strand, the different categories are presented, and for each category it is clarified whether the learning gains were, according to the students, (mostly) acquired in traditional or challenged-based courses. In addition, students’ explanations from their interviews are added to clarify their learning gains.

The reflections of eight participants who followed the learning trajectory “Responsible innovation in a global context” were analysed using our learning gains framework for engineering education. First, we divided the reflections in different categories, each representing a different unit of analysis. Subsequently, each unit of analysis was labeled with an element from the learning gains framework. All comments could be labeled via the elements of our learning gains framework.

RESULTS

For each strand, the interview results (including the “pie chart drawings”) are presented in a table, and subsequently, the written reflections on the challenge-based learning trajectory “Responsible innovation in a global context” are described.

The Disciplinary Conceptual and Procedural Knowledge Strand

This strand refers to knowledge of mathematics and sciences, fundamental knowledge regarding engineering, (engineering) subject matter knowledge, and disciplinary procedural knowledge. Table 1 shows that the interviewed students mentioned learning gains that could be categorized as theoretical knowledge and applying theory in models/graphs/programs. Most students mentioned learning gains acquired in traditional courses.

Table 1. Results on Disciplinary Conceptual and Procedural Knowledge

Traditional/ CBL	**Element**	**Example quote**
Traditional	Theory/basic knowledge	Steven (Mechanical Engineering) about the need for knowledge [in this case acquired in a traditional course] to do a DBL project: "You really have to understand thermodynamics to calculate with heath."
	Programming/ modelling	Peter (Applied Mathematics) about a traditional course with application elements: "You use data to make graphs and to interpret it."

In the written reflections of the CBL learning trajectory "Responsible innovation in a global context", just a few students mentioned learning gains regarding (engineering) subject matter knowledge, such as knowledge on responsible innovations.

The General Cognitive Learning Strand

This strand consists of cognitive learning, such as analytical reasoning, problem solving, system thinking, critical thinking, and investigation and design. Table 2 shows that the interviewed students perceived learning gains in both traditional and CBL courses.

Table 2. Results on General Cognitive Learning

Traditional/ CBL	**Element**	**Example quotes**
Traditional/ CBL	Critical thinking	Kim (Applied Mathematics) about a traditional course: "I noticed (…), you learn a way of thinking and proving things. You learn not to accept everything. In high school it was like: ok, differentiate this. But now you think: wat does that mean. Are you allowed to do that?" Mandy (Industrial Design about a DBL course: "When we design something, that you think: is this really a good idea or should it be different. (…) That you really think about…, whether you made the right decision."
CBL	Research	Rachel: (Industrial Design): At [a DBL course], there we have to do pilots too and do research with participants.
	Design (Scrum)	Walter (Computer Science and Engineering): "I was made to be the Scrum master. So, I went to the training and learned about Scrum, and I did the training again, because this quartile, I am a tutor for that course."

Students’ own written reflections regarding the CBL learning trajectory “Responsible innovation in a global context” presented additional elements of cognitive learning, such as analytical reasoning, system thinking, and CDIO (with a focus on design).

The Affect, Thought and Learning Strand

This strand refers to attitudes and thoughts about learning, such as taking initiative, perseverance and lifelong learning. In addition, it includes ethics, responsibilities of an engineer, and taking into account the external, societal, and environmental context. Table 3 shows that students, who did not know about the content of this strand, mentioned learning gains in their interviews regarding self-direction and responsibilities, ethics, and taking into account the social context.

Table 3. Results on Affect, Thought and Learning

Traditional/ CBL	**Element**	**Example quote**
Traditional	Ethics	Irene (Sustainable Innovation): “That you know how to look at ethical problems. (…) You are [usually] really busy with: there has to be a result and your technology or innovation has to work. But why ethics is important, is that you think more about what you are doing and why.”
Traditional/ CBL	Taking into account the social context	Ann (Sustainable Innovation): “All the courses, for Sustainable Innovation, that I have to take”.
CBL	Planning and taking responsibility	Mike (Mechanical Engineering): “I also learned a lot during the DBL projects that we do at the faculty Mechanical Engineering. (…) But also taking responsibility for a specific part. You are responsible for finishing that.”

The written reflections from the CBL learning trajectory “Responsible innovation in a global context” revealed comments on (a positive) attitude, reflection, and taking into account the social, political, economic and/or ecological context.

The Teamwork and Communication Strand

This strand focuses on teamwork, communications (e.g., written, oral), and communication in foreign languages. In the interviews (see Table 4), soft skills, such as presenting and academic writing were acquired in traditional and CBL courses, and teamwork skills were acquired during CBL.

Table 4. Results on Teamwork and Communication

Traditional/ CBL	Element	Example quote
Traditional/ CBL	Presentation and communication skills	Steven (Mechanical Engineering) about DBL projects: “You also learn to present. You learn soft skills with these projects, because you have to present quite a bit.” Ann (Sustainable Innovation): “We have these skills [classes, such as presenting] that we have to pass.”
CBL	Teamwork	Flora (Sustainable Innovation): “One of the biggest challenges for me was the intra-team collaboration. I had never worked so closely together with two people on a project for this long. We had a very different point of view on our project, resulting in discussions every now and then. The differences between us, however, have also strengthened our group work. I have learned from both [name student] as well as [name other student], and the collaboration within our group.”

Regarding the CBL learning trajectory “Responsible innovation in a global context”, students mentioned communication with team members as learning gains in their written reflections.

The Entrepreneurial Learning Strand

The entrepreneurial learning strand addresses the enterprise and business context, leading engineering endeavors, and entrepreneurship. In the interviews (see Table 5), students mentioned learning gains regarding collaboration and communication with companies during CBL.

Table 5. Results on Entrepreneurial Learning

Traditional/ CBL	Element	Example quote
CBL	Collaboration/ communication with companies	Charlotte (Applied Mathematics): “The most interesting, I thought, was getting experience with how to deal with companies and what they expect of you. (…) At a certain moment, you have the CEO of the company, who says: ‘I can help you.’ That is really nice. But you also have another company that did not reply at all. And then you have to think about a solution for that.”

In the written reflections on the CBL learning trajectory “Responsible innovation in a global context”, the students mentioned collaborating and communicating with outside stakeholders.

CONCLUSION AND DISCUSSION

In order to answer this study’s research question *Which (kinds of) learning gains do engineering students perceive in challenge-based learning versus traditional learning*, we interviewed 13 students about their learning gains at the university. In the data analyses, we differentiated between learning gains related to a) traditional and b) challenge-based courses (including DBL). In addition, we analyzed reflection forms that eight students wrote about the challenge-based learning trajectory “Responsible innovation in a global context”. In Table 6, students’ self-reported learning gains in CBL and traditional learning are presented.

Table 6. Students’ Self-reported Learning Gains in CBL versus Traditional Learning

Framework strand	**Challenge-based learning**	**Traditional learning**
Disciplinary conceptual and procedural knowledge	(Engineering) subject matter knowledge	Theory Application of theory in models, graphs and programs
General cognitive learning	Analytical reasoning System thinking Conceiving, designing, implementing, operating Critical thinking Research/design	Critical thinking Research/design
Affect, thought, and learning	Self-direction and responsibilities Taking into account the social context Attitude Reflection	Ethics Taking into account the social context
Teamwork and communication	Teamwork Communication	Communication
Entrepreneurial learning	Communication and collaboration with stakeholders	-

The results from the interviews and written reflections on the challenge-based learning trajectory “Responsible innovation in a global context” have similarities: for example, the fact that learning gains regarding the disciplinary conceptual and procedural knowledge strand were mostly acquired in traditional courses and were mentioned the least of all five strands in the written reflections on the challenge-based learning trajectory. This result connects to the study of Malmqvist et al. (2015) who compared different CBL courses and found that students in the Challenge Lab course were, amongst others, positive about the contact with stakeholders, but did not experience enhancement in specialized knowledge. In another article (most of) the same authors did find positive values for acquiring specialized knowledge, but students differed in their opinion: there were also students who were not positive about their knowledge enhancement (Rådberg et al., 2020). Therefore, attention to disciplinary conceptual and procedural knowledge is important when developing and implementing a CBL course or learning trajectory.

Another similarity between the interviews and the written reflections on the challenge-based learning trajectory were the learning gains related to the entrepreneurial learning strand (communication and collaboration with stakeholders). The importance of involving stakeholders is addressed by other researchers as well (Membrillo-Hernández et al., 2019), as this contributes to the formulation of realistic and complex challenges.

In summary, first, it seems advisable to further increase challenge-based learning at TU/e, as students value collaboration with companies on a real-life project. Second, it can be concluded that CBL courses did not seem to fulfil all learning gains intended in the curriculum, and that a mixture of CBL and (parts of) traditional courses appear to be beneficial for engineering students throughout their bachelor years.

Limitations and Recommendations

Although we were able to investigate the learning gains of 13 students in depth, we recommend to investigate a larger number of students to acquire more information on students' learning gains in traditional versus challenge-based courses.

During our interviews, we asked students about their learning gains at the university. In our data analysis, we differentiated between traditional and challenge-based courses. As the reflections of the students on the learning trajectory "Responsible innovation in a global context" provided detailed information about their learning gains, a recommendation for future research is to investigate several challenge-based courses in depth and to determine students' learning gains in these courses.

In addition, most of our participants were second year Bachelor students. For future research, we recommend to include students that are further along in their studies and have more experience with both traditional and challenge-based courses.

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BIOGRAPHICAL INFORMATION

Martina van Uum is a postdoc researcher and teacher at the Eindhoven School of Education of the Eindhoven University of Technology in the Netherlands. Her current research focus is on students' learning gains in (innovative) higher engineering education with special interest in challenge-based learning. Together with Birgit Pepin, she developed and validated a learning gains framework for engineering education based on the CDIO framework and inspired by other frameworks.

Birgit Pepin is a full Professor of Mathematics/STEM Education at the Eindhoven School of Education of the Eindhoven University of Technology in the Netherlands. Her teaching and research focus on mathematics curriculum materials (including digital curriculum resources), and teacher pedagogy and professional learning, especially in mathematics education in secondary schooling and in engineering higher education.

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