International Journal of Science and Mathematics Education (2022) 20:277–297
https://doi.org/10.1007/s10763-021-10167-0

Towards Inquiry-Based Flipped Classroom Scenarios: a Design Heuristic and Principles for Lesson Planning

Stefanie Schallert[1] · **Zsolt Lavicza**[1] · **Ellen Vandervieren**[2]

Received: 27 August 2020 / Accepted: 8 February 2021/Published online: 26 February 2021

Abstract

The effectiveness of flipped classroom approaches can be improved by combining it with other pedagogical models such as inquiry-based learning. Implementing inquiry-based learning in flipped classroom scenarios requires teachers to plan arrangements for in- and out-of-class activities carefully. In this study, a design heuristic based on the 5E inquiry model was developed to support teachers' practice of planning inquiry-based flipped classroom lessons. Following a design-based research approach, the design heuristic progressed through two cycles within 2 years. The design heuristic was implemented in both cycles in an online professional development course for secondary mathematics teachers. In the first cycle, 18 lesson plans were collected and analysed using the 5E lesson plan scoring instrument. Results showed that the design heuristic helped teachers to set up lesson plans for flipped classroom scenarios which were mostly in line with the 5E model. However, the evaluation phase was insufficiently addressed. Revision decisions were made at the end of the first cycle, and the design heuristic was revised and re-implemented in a second cycle. Results of the second cycle showed another 19 participating teachers who also struggled in choosing appropriate assessment techniques, an issue which could not be resolved with the proposed design heuristic. This paper describes the development of the design heuristic as well as relevant design principles for inquiry-based flipped classroom scenarios. The proposed design heuristic is not domain specific. Hence, further research could examine its use in other subjects or interdisciplinary as inquiry-based flipped classroom approaches are one of the emerging pedagogies.

Keywords 5E model · Design research · Mathematics education · Student-centred learning · STEM education

✉ Stefanie Schallert
stefanieschallert@gmail.com

Extended author information available on the last page of the article

Introduction

Teacher professional development courses for implementing flipped classroom approaches in science, technology, engineering and mathematics (STEM) education have been gaining popularity and relevance during the past decade. In these courses, teachers mostly become familiar with traditional ways of flipping classes, where information transmission is done through instructional videos before class, and the gained in-class time is used for various student-centred learning activities (Wasserman, Quint, Norris, & Carr, 2015). To maximise the effectiveness of flipped classroom scenarios, a current meta-analysis (Zheng, Bhagat, Zhen, & Zhang, 2020) recommends combining flipped classroom approaches with other pedagogical models like inquiry-based learning. In STEM education, inquiry-based learning can be ideally implemented in flipped classroom scenarios because the freed-up in-class time can be used for letting students conjecture, explore, communicate and justify problem solutions (Love, Hodge, Corritore, & Ernst, 2015). Especially in mathematics education, the foundation of all sciences, fostering learning through inquiry is crucial for the development of problem-solving skills (Goos, 2004). Being able to solve complex problems is also an important STEM competence (Jang, 2016).

There are various possibilities of enabling learning through inquiry by flipping a class. For instance, in a productive failure-based flipped classroom (Kerrigan, 2018; Song & Kapur, 2017), students are required to tackle different problems in class, even if they encounter failure. Afterwards, students are asked to watch a video at home to consolidate their findings instead of first accessing a video explaining problem solutions as homework followed by application during the lesson in a traditional flipped classroom scenario. For setting up an inquiry-based flipped classroom scenario, teachers need to plan on how to arrange in-class and out-of-class phases carefully. Recent research (Weinhandl, Lavicza & Houghton, 2020) indicates essential aspects for introducing STEM teachers and especially mathematics teachers (Cevikbas & Kaiser, 2020; Weinhandl & Lavicza, 2019) to flipped classroom approaches. However, there is still a lack of research investigating how to support STEM teachers' lesson planning practice for inquiry-based flipped classroom scenarios.

The study presented in this paper aimed at a twofold yield. On the one hand, we intended to develop a design heuristic for inquiry-based flipped classroom scenarios to support secondary mathematics teachers' lesson planning practice. On the other hand, we aimed to contribute to theory with design principles for inquiry-based flipped classroom scenarios. We opted for a design-based research approach (e.g. Bakker, 2018; The Design-Based Research Collective, 2003; Wang & Hannafin, 2005) to develop the design heuristic and the underpinning theory synchronously through an iterative process, which consisted of two sequential design-based research cycles. In both cycles, the design heuristic was implemented in the same online professional development course for secondary mathematics teachers in Austria. In total, 37 lesson plans using the design heuristic were collected and analysed for this study.

This paper is organised as follows. First, we will present the theoretical background underlying the design heuristic as well as the developed design heuristic itself. We then will describe the overall research design. Subsequently, we will report and discuss results, including respective revision decisions of each cycle. Next, we will present a set of design principles for inquiry-based flipped classroom scenarios which evolved through the design-based research project over 2 years. Finally, we will conclude with a summary of the findings, limitations of this study and ideas for further research.

Theoretical Background

In this section, we outline rationales behind the design of the proposed design heuristic and present relevant literature supporting the used models and definitions. In the design heuristic, we merge the 5E inquiry model (Bybee et al., 2006) with Abeysekera and Dawson's (2015) definition of a flipped classroom. We refer to this approach as the 5E-based flipped classroom.

Flipped Classroom Approaches. Abeysekera and Dawson (2015) characterise a flipped classroom as follows. Out-of-class phases are merely used for information transmission, and during class, learners are required to be actively involved in student-centred learning activities. To engage in in-class activities, learners should accomplish both pre- and post-class activities. We based the design heuristic on the aforementioned definition since information transmission phases of a flipped classroom are not restricted to be implemented prior to class. This freedom of outsourcing direct instruction is crucial for fostering learning through inquiry in flipped-classroom scenarios. Because according to Kapur's (2010) theory of productive failure, students' knowledge consolidation could be enhanced by letting them explore problem solutions before instructing them on it.

Flipped classroom approaches are often associated with video-based learning (Lo, 2018). Lecture videos are the most prominent example, although videos engaging students in the upcoming learning sequence can also be assigned as homework (De Araujo, Otten & Birisci, 2017). Especially inquisitive videos can be suitable to implement in inquiry-based flipped classroom scenarios because an inquisitive video starts with presenting a problem or phenomenon in-depth, followed by discussing various potential solutions or probing questions without anticipating final solutions or answers (Voigt, Fredriksen, & Rasmussen, 2020). Abeysekera and Dawson (2015) did not include in their definition the use of technology in flipped classroom scenarios. As technology-supported instruction can positively affect students learning mathematics and science (Hillmayr, Ziernwald, Reinhold, Hofer, & Reiss, 2020), we included examples for using technology such as interactive videos in the descriptions of the design heuristic. But we think there are many different ways of flipping a class, not solely with information transmission via videos. For example, information transmission can also be pursued by listening to podcasts or reading related texts.

Previous studies have already shown that flipped classroom approaches can improve student performance in science education (Sezer, 2017) as well as in mathematics education (Charles-Ogan & Williams, 2015; Wei et al., 2020). A recent study (Cevikbas & Kaiser, 2020) regarding flipping mathematics classes concludes that well-designed flipped classroom scenarios can support students' mathematical thinking and understanding by applying differentiated teaching strategies. In this paper, we are investigating the design of inquiry-based flipped classroom scenarios and present the development of a design heuristic supporting teachers' lesson planning practice. Besides the abovementioned flipped classroom definition, we used the 5E inquiry model for setting up the design heuristic and outline this model in the following section.

The 5E Inquiry Model. The 5E model (Bybee et al., 2006) is an instructional model, where learning through inquiry follows five phases. The five phases are called (i) engagement, (ii) exploration, (iii) explanation, (iv) elaboration and (v) evaluation. Following the 5E model, an inquiry process starts with engaging and motivating students. Depending on the teachers' choice, questions to be investigated can be propounded or developed together with the learners. Next, learners should explore new phenomena to construct their understanding. Based on their experiences during exploration, learners should articulate and defend their findings. Teachers may help students to link their findings to relevant theories or concepts. The phase of elaboration follows the explanation. During the elaboration, students are given additional activities, which should facilitate the transfer to closely related but new situations to generalise concepts, processes or skills. In the last phase, students should be given the opportunity to evaluate their understanding by using their acquired skills. Additionally, educators should assess students' learning and give feedback, whereby the evaluation can result from the culmination of the formative assessment activities applied throughout the sequence.

We utilised the 5E model for the development of the design heuristic because the five essential features of classroom inquiry (National Research Council, 2000) can be determined in 5E lessons as exemplified in Table 1. The five essential features of classroom inquiry are: (i) *the learner's engagement in scientifically oriented questions*, (ii) *priority of evidence in response to questions*, (iii) *formulation of explanations from evidence*, (iv) *explanations connected to scientific knowledge and* (v) *communication and justification of explanations* (National Research Council, 2000, p. 29).

The applicability of the 5E model has been researched extensively. The 5E model was originally developed for science education, although previous research (Omotayo & Adeleke, 2017; Tuna & Kacar, 2013) has already examined its applications in other subjects such as mathematics with promising results. Findings of numerous studies (e.g. Bilgin, Coşkun, & Aktaş, 2013) indicate that using the 5E model in STEM education can have a positive effect on students' achievement.

Table 1 Essential features of classroom inquiry in 5E lessons

Essential feature of classroom inquiry	Example in 5E lesson
The learner's engagement in scientifically oriented questions	During the engagement, teachers introduce a problematic situation or phenomenon, define a problem or develop a question for investigation together with the students.
Priority of evidence in response to questions	Teachers support students' exploration process via informal assessment conversations.
Formulation of explanations from evidence	During exploration, teachers encourage students to start formulating their explanations based on their findings. Additionally, during elaboration, students might formulate explanations from evidence by applying what they have learned.
Explanations connected to scientific knowledge	In the explanation phase, teachers assist students in linking their explanations to relevant concepts or theories.
Communication and justification of explanations	Throughout the phase of explanation, students are asked to verbalise and substantiate their explanations. Also, in the evaluation phase, students evaluate their understanding by giving and justifying explanations.

The 5E-Based Flipped Classroom Approach. Combining the 5E model with flipped classroom scenarios could free up more in-class time for student-centred activities because of the outsourced information transmission. Few researchers have already investigated 5E-based flipped classroom settings. Lo (2017) exemplifies the use of a flipped classroom grounded in the 5E model in history education and highlights the need for more research.

Regarding STEM education, Aşıksoy and Ozdamli (2017) investigated a 5E-based flipped classroom using a mixed-method approach on a physics course involving 94 engineering students. Results of this randomised control trial show that student achievement in the 5E-based flipped classroom group was significantly higher than in the control group, where only the 5E model was implemented. Furthermore, students' perceptions were gathered through semi-structured interviews. Findings indicated that learning in the 5E-based flipped classroom seemed more meaningful to students. Moreover, students reported that the 5E-based flipped classroom approach helped them to grasp the connection between real life and physics principles more easily as they had more time during class to discuss this connection. In contrast, a quasi-experimental study (Jensen, Kummer & Godoy, 2015) investigating the impact of the 5E-based flipped classroom in biology education on 108 students came to other results. There was no significant difference between the flipped 5E class and the non-flipped 5E class regarding students' satisfaction and achievements. Jensen et al. (2015) concluded that learning gains in either condition may be the result of the active learning approach implemented rather than flipping the class. The discrepancy between the two aforementioned studies regarding the impact of the 5E-based flipped classroom approach on student achievement and attitudes can be explained to result from the way the approach was applied. In the Aşıksoy and Ozdamli (2017) study, the non-flipped 5E class just had one lesson without homework focusing on all 5E phases, whereas in the Jensen et al. (2015) study, homework was assigned after the in-class phase in the control group. Therefore, in the Jensen et al. (2015) study, the experimental and control group had the same amount of time for the active content attainment.

In mathematics education, the productive failure-based flipped classroom (Kerrigan, 2018; Song & Kapur, 2017) could be seen as a further development of traditional flipped classroom approaches towards a 5E-based flipped classroom. In a productive failure-based flipped classroom, learners start with tackling problems in-class, even if they encounter failure but supported by a teacher. To consolidate their findings, they watch an explanatory video at home. Therefore, a productive failure-based flipped classroom (Song & Kapur, 2017) addresses only the first three phases of the 5E model, namely engagement, exploration and explanation. Song and Kapur (2017) compared, in a quasi-experimental study, the traditional flipped classroom, where students receive direct instruction as homework followed by applying their knowledge in class, with the productive failure-based flipped classroom. Findings show that the productive failure-based flipped classroom positively influenced mathematics students' conceptual understanding.

Design Heuristic for Lesson Planning of 5E-Based Flipped Classroom Scenarios. As we aimed to enhance teachers' lesson planning practice for inquiry-based flipped classroom scenarios, we developed a design heuristic. The idea of creating a design heuristic for lesson planning was inspired by Janssen, Tigelaar, and Verloop's (2009) study. In their study, Janssen et al. (2009) developed and evaluated a design heuristic for biology lessons aimed at teaching for understanding. Findings indicate that the design heuristic helped most student teachers setting up lesson plans satisfactory according to criteria for problem-posing lessons.

The basis for our design heuristic formed the 5E inquiry model (Bybee et al., 2006) and Abeysekera and Dawson's (2015) definition of a flipped classroom. For each 5E phase, the design heuristic (see Table 2) suggests out-of-class and in-class activities. According to Abeysekera and Dawson's (2015) definition of a flipped classroom, we incorporated activities focusing mainly on information transmission and passive learning activities in the out-of-class phases. Student-centred learning activities such as collaborative problem solving, where students are supposed to be active, have been included in the in-class phases. The proposed design heuristic constitutes a rough blueprint for setting up 5E-based flipped classroom scenarios, and teachers do not have to always use out-of-class activities together with in-class activities in each 5E phase.

Table 2 presents the design heuristic for 5E-based flipped classroom scenarios, which we developed in a design-based research study consisting of two cycles. At the beginning of the study, we identified and analysed the problem in the educational context: Austrian mathematics teachers need help implementing learning through inquiry in flipped classroom scenarios. Based on a literature review, we set up a prototype of our design heuristic. Consequently, we implemented the first version of the design heuristic in an online professional development course. Next, we analysed the collected lesson plans and reviewed a body of literature to revise the design heuristic. Informed by already existing design principles for flipped classroom scenarios, we set up tentative design principles for inquiry-based flipped classroom scenarios. Based on the results of the first cycle, we revised the prototype and re-implemented the design heuristic in the same professional development course half a year later. Again, we analysed the collected lesson plans and revised the design heuristic as well as design principles according to the results of the second cycle. In Table 2, components of the design heuristic that were initially part of the prototype are shown in bold. The components shown in italics indicate they were added or revised in different design research cycles. The numbers in brackets specify the design research cycle a component was added or revised.

Research Questions. The following two research questions are to be addressed in this paper:

(1) To what extent does the proposed design heuristic support secondary mathematics teachers in developing flipped classroom lesson plans that are in line with the 5E inquiry model?
(2) How should flipped classroom scenarios be designed to foster inquiry-based learning in secondary mathematics education?

Methodology

In the following, we elucidate the research design, including an overview of the research phases, context, participants, data collection and data analysis.

Table 2 Design heuristic for 5E-based flipped classroom scenarios

5E phase	Out-of-class activities	In-class activities
1. Engagement	*Based upon the objective(s) prior knowledge should be activated,* e.g. *using an interactive video with integrated quiz questions. (1)* **Teacher introduces the educational scenario/phenomenon to provoke curiosity.** **Students go through the provided material at their own pace and note any questions that arise.**	**Teacher leads classroom discussion, and the question(s) for investigation is/are developed.** **Students engage in the classroom discussion.**
2. Exploration	*Teacher provides primary sources for exploration such as inquisitive videos. In inquisitive videos, a problem is discussed in detail without anticipating final solutions. (2)* *Students prepare for class by inspecting the primary sources presented. (2)*	**Teacher supports the exploration process,** *offers valuable real-time feedback* (e.g. *informal assessment conversations) (1)* **and encourages learners to formulate findings based on their experiences.** **Students explore the learning environment and** *use the evidence to formulate tentative explanations,* e.g. *in a science journal. (1)*
3. Explanation	**Teacher introduces relevant concepts or theories that might have escaped students' notice or that students are not familiar with to foster deeper understanding, e.g. using video, textbook materials.** *Different approaches should be used to explain and illustrate concept(s) or skill(s). (2)* **Students study the provided material and compare it with their explanations.**	**Teacher and students utilise the concept(s) and the experience(s) to describe and explain the phenomenon and answer the initial question(s).** *The discussion or activity allows the teacher to assess students' present understanding of concept(s) or skill(s). (1)*
4. Elaboration	**Teacher describes new, but closely related problems, e.g. using video and/or textbook materials.** *The activities should stimulate learners to find real-life connections. (1)* **Students get the task to identify new but closely related situations.**	**Teacher promotes elaboration.** *By providing differentiated tasks, different achievement levels of learners can be respected. (2)* **Students apply the knowledge gained to solve new, but closely related problems.**
5. Evaluation	**Teacher provides self-assessment for learners.** **Students engage in self-assessment tasks to reflect on their learning process.**	**Teacher evaluates students' progress towards achieving educational goals.** *The evaluation results from the culmination of the formative assessment activities applied throughout the sequence. (2)* *The evaluation criteria should be clear, appropriate and measurable* (e.g. *use of rubrics with scoring criteria). (1)*

Design-Based Research. In this study, we apply Wang and Hannafin's (2005) definition of design-based research. Design-based research is defined as 'a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories' (Wang & Hannafin, 2005, pp. 6–7). We employed a design-based research approach to improve secondary mathematics teachers' lesson planning practice with the proposed design heuristic and develop a theory for the design of inquiry-based flipped classroom scenarios simultaneously through cycles of designing, testing and reflecting.

According to Lo and Hew (2017), design-based research studies conducted over a long period could lead to more profound guidelines on how to beneficially apply flipped classroom approaches in comparison to experimental research designs. Many studies (Cheng, Ritzhaupt, & Antonenko, 2019) have already investigated flipped classrooms in one-off experiments. Still, now there is the need to explore different ways of flipping a class (Otten, de Araujo, & Sherman, 2018). Nevertheless, findings of one-off experiments can provide first insights. In our case, results of the quasi-experimental study of Song and Kapur (2017) comparing the productive failure-based flipped classroom with the traditional flipped classroom formed the base for our research because their findings indicate that it matters if information transmission is done before or after the in-class activities. Mathematics students who received direct instruction as homework after tackling problems themselves during class showed better results in terms of conceptual knowledge.

Phases of the Present Design-Based Research Study. Following a design-based research approach (Wang & Hannafin, 2005), the present study progressed through two design research cycles over 2 years (see Fig. 1). In our case, two design research cycles were sufficient to achieve an optimal solution, which can be described as 'a satisfying balance between ideal ('the intended') and realisation' (Plomp, 2013, p. 17).

Findings of the first design-based research cycle, including an in-depth qualitative analysis of the collected lesson plans and the discussion of a lesson plan example, are published in Schallert, Lavicza and Vandervieren (2020).

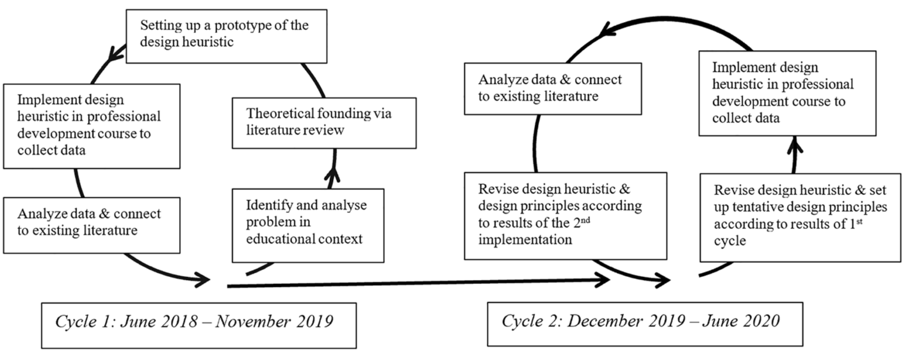

Fig. 1 Overview of activities in the two sequential design-based research cycles

Context and Participants. The study reported in this paper was carried out in Austria. The first author of this paper has several years of experience in face-to-face as well as online teacher professional development for flipped classroom approaches. Over the years, the first author noticed mathematics teachers struggling in setting up lesson plans for inquiry-based flipped classroom scenarios. Most teachers would adhere to traditional flipping, where information transmission is done before class. Therefore, we aimed to develop a design heuristic for lesson planning to support teachers in implementing learning through inquiry in flipped classroom scenarios. We implemented the design heuristic in both design research cycles within an online professional development course, which was offered at the Austrian University College of Virtual Teacher Education. In Austria, online professional development is becoming increasingly popular since teachers can pursue in-service training irrespective of place and time.

In both design research cycles, participants were secondary mathematics teachers, who participated voluntarily. Participants of the first design research cycle were 22 teachers. Eighteen teachers completed the online professional development course and agreed their uploaded lesson plan would be analysed for this study. In the second design research cycle, 24 teachers participated in the online course. From the 24 participating teachers, 19 teachers completed the online course and gave informed consent to the use of their lesson plan for research purposes. Participants in both cycles did not provide their demographic information. Before data analysis, each lesson plan was assigned a number. Therefore, personal identification was removed, and data was treated confidentially.

Procedure of the Online Professional Development Course and Data Collection. The 3-week-long online professional development course with an estimated total workload of 15 h was carried out at the University College of Virtual Teacher Education in Austria. This course aimed to introduce participating teachers to the 5E-based flipped classroom approach. We designed and configured the online course on the learning management system Moodle, and the quality of the online course was ensured by the University College of Virtual Teacher Education quality control.

For selecting the course material, current research findings were considered. As suggested by Tuan, Yu, and Chin (2017), we provided video tutorials explaining relevant concepts and lesson plan examples. Weinhandl and Lavicza (2018) investigated crucial aspects when introducing teachers to flipped classroom approaches in Austria. One crucial aspect was to let teachers complete the professional development course with a product, which reflects their learning processes. In our case, the product reflecting their learning processes was a lesson plan individually designed and developed by participating teachers. Additionally, Weinhandl and Lavicza (2018) stated that course design should foster cooperative learning among course participants. To facilitate cooperative learning, the online course was assisted by the first author. The first authors' tasks included giving feedback on assignments, moderating the online forums, answering occurring questions and motivating the participating teachers (see Table 3). Throughout the study, we worked closely together with the participating teachers to refine the proposed design heuristic and design principles, what is crucial for design-based research (Amiel & Reeves, 2008).

Table 3 presents the six steps taken to familiarise participating teachers with the design heuristic and to let them plan lessons on a self-selected topic using the design

Table 3 Steps in the procedure of having teachers use the design heuristic for lesson planning

Step	Description
Step 1	Introduce teachers to the 5E inquiry model with text material and online activities.
Step 2	Introduce teachers to flipped classroom approaches with video tutorials and online activities.
Step 3	Introduce teachers to the design heuristic for 5E-based flipped classroom scenarios with text material and online activities.
Step 4	Present six lesson plan examples set up by the authors and let teachers discuss the examples according to guiding questions in online forums.
Step 5	Teachers set up a lesson plan on a self-selected topic using the design heuristic and upload it to the learning management system. The lesson plans were required to contain a complete materials list and a detailed description of the planned out-of-class as well as in-class activities for each 5E phase. Teachers were also asked to state lesson objectives aligning with the teachers' respective school curriculum. During the design phase, no support was provided by the author, who assisted the online course.
Step 6	Teachers receive feedback on their lesson plans from the other participants and the author, who assisted the online course.

heuristic. Lesson plans developed in the fifth course step (see Table 3) were collected and used for the analysis in this study.

Data Analysis. Within this design-based research study, we carried out a document analysis (Bowen, 2009) of written lesson plans. We collected written lesson plans as the inclusion of their detailed descriptions, materials and references makes them fruitful for our study. As written text was our main data source and the participating teachers were not supported during the design phase of the lesson plans, interaction effects between participants and researchers should not occur (Kondracki, Wellman, & Amundson, 2002).

For analysis, we used the 5E lesson plan scoring instrument (Goldston, Dantzler, Day, & Webb, 2013). Using a psychometric approach, Goldston et al. (2013) developed and verified the 5E lesson plan scoring instrument (hereafter as 5E ILPv2) with 224 pre-service science teachers. The 5E ILPv2 (see Table 4) is a solid instrument for evaluating written 5E lesson plans because of the total instrument reliability estimate of 0.98. The 5E ILPv2 contains in total 21 items for the different 5E phases, including engage (4 items), explore (4 items), explain (6 items), elaborate (3 items) and evaluate (4 items). Furthermore, the 5E ILPv2 employs a 5-point Likert scale ranging from 0 to 4 points per item and employs five scoring criteria as follows: unacceptable (score 0), poor (score 1), average (score 2), good (score 3) and excellent (score 4).

We adopted the 5E ILPv2 to detect strengths and weaknesses of the design heuristic and to revise the design heuristic systematically. Because of the small sample size (first cycle $N = 18$, second cycle $N = 19$), we do not present the results with the used 5-point Likert scale and rely on descriptive statistics. We rather clustered the scoring together into 'fulfilled item' and 'failed item'. If, for a particular item, a lesson plan got a score from 2 to 4 (average to excellent), it fulfilled the item. If it got a score lower than 2 (unacceptable or poor), it failed the item. In both design research cycles, the first author of this paper scored all lesson plans with the 5E ILPv2. To ensure reliability, we asked in both cycles, another experienced teacher educator to get familiar with the 5E ILPv2

Table 4 Evaluation of lesson plans according to the 5E scoring instrument in both design research cycles

5E ILPv2 item	Item description	Percentage of lesson plans that fulfilled the item in the 1st cycle (N=18)	Percentage of lesson plans that fulfilled the item in the 2nd cycle (N=19)
Engage item 1	The engage phase elicits students' prior knowledge (based upon the objectives).	56%	79%
Engage item 2	The engage phase raises student interest/motivation to learn.	94%	100%
Engage item 3	The engage phase provides opportunities for student discussion/questions (or invites student questions).	78%	84%
Engage item 4	The engage phase leads to the exploration phase.	83%	95%
Explore item 1	During the exploration phase, teachers present instructions.	89%	95%
Explore item 2	Learning activities in the exploration phase involve hands-on/minds-on activities.	94%	95%
Explore item 3	Learning activities in the exploration phase are student-centred.	94%	95%
Explore item 4	The inquiry activities of the exploration phase show evidence of student learning (formative authentic assessment).	56%	84%
Explain item 1	There is a logical transition from the exploration phase to the explanation phase.	89%	89%
Explain item 2	The explanation phase includes teacher questions that lead to the development of concepts and skills.	89%	89%
Explain item 3	The explanation phase includes mixed divergent and convergent questions for interactive discussion facilitated by teacher and/or students to develop concepts or skills.	78%	79%
Explain item 4	The explanation phase includes a complete explanation of the concept(s) and/or skill(s) taught.	89%	89%
Explain item 5	The explanation phase provides a variety of approaches to explain and illustrate concept or skill.	78%	74%
Explain item 6	The discussion or activity during the explanation phase allows the teacher to assess students' present understanding of concept(s) or skill(s).	83%	95%
Elaborate item 1	There is a logical transition from the explanation phase to the elaboration phase.	67%	84%
Elaborate item 2	The elaboration activities provide students with the opportunity to apply the newly acquired concepts and skills into new areas.	94%	89%

Table 4 (continued)

5E ILPv2 item	Item description	Percentage of lesson plans that fulfilled the item in the 1st cycle ($N = 18$)	Percentage of lesson plans that fulfilled the item in the 2nd cycle ($N = 19$)
Elaborate item 3	The elaboration activities encourage students to find real-life connections with the newly acquired concepts or skills.	56%	63%
Evaluation item 1	The lesson includes summative evaluation, which can consist of a variety of forms and approaches.	44%	47%
Evaluation item 2	The evaluation matches the objectives.	39%	47%
Evaluation item 3	The evaluation criteria are clear and appropriate.	33%	37%
Evaluation item 4	The evaluation criteria are measurable (i.e. using rubrics).	33%	32%

and score all lesson plans accordingly. The second scorer was working at the University College of Virtual Teacher Education but was not at all involved in this study apart from scoring. When differences in scoring occurred, they were discussed until consensus was reached.

Results and Discussion

Applying the 5E ILPv2 (Goldston et al., 2013) in both design research cycles, we analysed to what extend the collected lesson plans for flipped classroom scenarios were in line with the 5E model. According to the results of each cycle, we made revision decisions for the design heuristic (see Table 2). Table 4 shows the results of using the 5E ILPv2 to analyse the collected lesson plans of the first and second design research cycle.

The results of both design research cycles, including the revision decisions, are discussed subsequently. However, we will not address each 5E ILPv2 item. Instead, we will focus on the items that have led to revision decisions.

According to Table 4, in the first cycle, only 56% of the lesson plans addressed engage item 1 adequately. Eliciting prior knowledge is essential since knowledge construction is based on prior knowledge (Borko & Putnam, 1996). After the first cycle, we added in the design heuristic the activation of prior knowledge in the engagement's out-of-class phase. We suppose that this change has led to the result that 79% of participating teachers planned to activate prior knowledge in the second cycle.

As shown in Table 4 regarding explore item 4, 56% of teachers participating in the first cycle planned to assess students' learning during exploration. Evaluation should be an ongoing process and should not be seen as a distinct phase at the end of a 5E learning cycle (Bybee, 2009). To address evaluation in the exploration phase in the design heuristic, we decided to cite informal assessment conversations (Ruiz-Primo & Furtak, 2007) as an example for informal evaluation. Furthermore, we included science journals as an example to let students document their inquiry process and formulate tentative explanations. We assume that due to these revisions of the design heuristic, 84% of lesson plans fulfilled explore item 4 in the second cycle. To address also evaluation in the explanation phase, we addressed in the explanation's in-class phase assessing students' present understanding during explanatory activities after the first cycle.

The majority of teachers in both cycles intended to present instructions during exploration in-class (see explore item 1). To give teachers an idea how to use out-of-class phases presenting instructions during exploration, we included inquisitive videos (Voigt et al., 2020) as an example for primary sources in the design heuristic.

In the second cycle, 74% of the lesson plans addressed explain item 5 satisfactorily. Still, some teachers intended to just provide a video for consolidation as homework; what seems to be in line with the productive failure-based flipped classroom approach (Song & Kapur, 2017). After the second cycle, we decided to address the explain item 5 in the design heuristic by adding a disclaimer saying various approaches should be used to explain and illustrate concepts or skills.

In the first cycle, the result of elaborate item 3 revealed the missing real-life connection in the description of the design heuristic's elaborate phase, what we considered in the revision of the design heuristic. Table 4 shows that in the second cycle, 63% of the lesson plans fulfilled elaborate item 3. We suspect finding elaborate activities stimulating learners to find real-life connections was yet tricky for some participating teachers. Teachers might need more support than just the proposed design heuristic to tackle elaborate item 3.

During lesson plan analysis in the second cycle, we noticed some teachers planned to provide differentiated tasks for various student levels in the elaboration phase. After the second cycle, we decided to add in the design heuristic's elaboration phase to respect the achievement levels of different students by providing differentiated tasks.

In both cycles, evaluation items 1–4 were not addressed adequately. After the first cycle, the disclaimer regarding the evaluation was added (see Table 2), but evaluation items 1–4 were still not addressed sufficiently in the second cycle. In addition, after the first cycle, rubrics were added as an example to assess students learning in 5E scenarios (e.g. Duran, 2003). Most teachers in the second cycle intended to monitor students' learning progress during exploration and intended to let students keep science journals during the phase of exploration and explanation. However, in the majority of lesson plans, descriptions of summative evaluation, including evaluation criteria, were missing. This finding seems to be in line with Harrison's (2014) finding saying teachers in inquiry-based learning scenarios usually focus on assessing students' learning during the exploration through observing learners. After the second cycle, we added a description regarding the summative evaluation to the design heuristic.

The majority of teachers planned to implement only a self-assessment tool at the end of their learning sequence. It seems as if most of the participating teachers in both cycles thought self-assessment only is sufficient for the phase of evaluation. According to Correia and Harrison (2019), teacher beliefs regarding inquiry-based learning influence their assessment practice. Teacher beliefs on inquiry-based learning might have also played a distinctive role in our study. We assume that our design heuristic alone was not sufficient to entirely help teachers in selecting appropriate assessment techniques and approaches for 5E-based flipped classroom scenarios.

Design Principles

Design-based research studies are conducted to contribute to the existing body of knowledge, not only to improve educational practice (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). Besides the presented design heuristic (see Table 2), design principles for inquiry-based flipped classroom settings evolved in the course of this design-based research study. For the format of the design principles, we adopted an approach for setting up design principles in design-based research studies proposed by Van den Akker (2013). An overview of the design principles is given in Table 5. The five essential features of classroom inquiry (National Research Council, 2000) are addressed in design principle numbers 3, 4, 5 and 6 (see Table 5). Design principle numbers 2 and 8 (see Table 5) are informed by design principles for flipped mathematics classrooms (Lo et al., 2017). The proposed design principles should act as guidelines for setting up inquiry-based flipped classroom scenarios in secondary mathematics education. Educators should also consider design principles for setting up flipped classroom scenarios in general. For instance, it is recommended to manage

Table 5 Eight design principles for setting up inquiry-based flipped classroom scenarios

If you want to design a flipped classroom scenario, which should foster students to learn mathematics through inquiry, you are advised to:	
Principle 1	Consider using pre out-of-class phases to provide connections between the content to be learned and prior topics fostering the activation of prior knowledge.
Principle 2	Use online exercises for formative assessment and to motivate students completing pre- and post-class activities.
Principle 3	Ensure the learner's engagement in scientifically oriented questions in-class or out-of-class.
Principle 4	Implement exploratory activities during class to support students with valuable real-time feedback.
Principle 5	Consider using post out-of-class phases for consolidation and connection to scientific knowledge.
Principle 6	Encourage learners especially in-class to articulate their findings because they should justify their answers.
Principle 7	Require students during class to apply their acquired knowledge or skills in solving differentiated tasks and tackling real world problems because learning should be meaningful to them.
Principle 8	Implement small group learning activities during class to facilitate peer-assisted learning.

the transition to a flipped classroom approach (Lo et al., 2017) as well as link in-class and out-of-class activities (Kim, Kim, Khera, & Getman, 2014).

In the following, the design principles on how to foster learning through inquiry in flipped classroom settings will be described in more detail.

Principle 1: Consider Using Pre Out-of-Class Phases to Provide Connections Between the Content to be Learned and Prior Topics Fostering the Activation of Prior Knowledge. Learners construct knowledge based on their prior knowledge (Borko & Putnam, 1996). Therefore, pre out-of-class phases in inquiry-based flipped classroom scenarios should be used for activating prior knowledge. Introductory material should stimulate learners to extend or revise their prior knowledge. For instance, introductory videos providing connections between the content to be learned and previous topics can be implemented at the beginning of the learning sequence (Voigt et al., 2020).

Principle 2: Use Online Exercises for Formative Assessment and to Motivate Students Completing Pre and Post-Class Activities. To fully benefit from in-class activities, learners are required to complete pre- and post-class activities (Abeysekera & Dawson, 2015). Online exercises such as quizzes with instant feedback can be used as self-assessment to promote students completing out-of-class activities. Also, most online exercises allow teachers to monitor their students' achievements and can be utilised for formative assessment in inquiry-based flipped classroom scenarios.

Principle 3: Ensure the learner's Engagement in Scientifically Oriented Questions In-Class or Out-of-Class. In inquiry-based flipped classroom scenarios, a learning process can be initiated by posing questions or problems. As an example, inquisitive videos discussing a problem or phenomenon in detail without anticipating final solutions or answers can be implemented before class (Voigt et al., 2020). It depends on the teacher's choice if the question for investigation is developed together during class or raised in a prior out-of-class phase. Either way, as an essential feature of classroom inquiry *the learner's engagement in scientifically oriented questions* should be considered.

Principle 4: Implement Exploratory Activities during Class to Support Students with Valuable Real-Time Feedback. Teacher guidance is crucial for letting students reinvent a mathematical concept within a flipped classroom scenario (Fredriksen, 2020). To support students during their exploration, obviously exploratory activities should be implemented in class. Informal assessment conversations (Ruiz-Primo & Furtak, 2007) could be used to evaluate students' understanding and offer students valuable real-time feedback. By using informal assessment conversations, the essential feature of classroom inquiry *students give priority to evidence in responding to questions* can be addressed.

Principle 5: Consider Using Post Out-of-Class Phases for Consolidation and Connection to Scientific Knowledge. Post out-of-class phases in inquiry-based flipped classroom scenarios can be used to facilitate consolidation. For consolidation, teachers can present relevant concepts or theories which might have escaped students' notice in post out-of-class phases (Song & Kapur, 2017). The outsourced information transmission should assist students in linking their explanations with their scientific knowledge and is in line with the essential feature of classroom inquiry *explanations connected to scientific knowledge*.

Principle 6: Encourage Learners Especially In-Class to Articulate Their Findings, Because They Should Justify Their Answers. Throughout the inquiry process, students should articulate their findings during class supported by teachers, who might help learners to find appropriate terms or concepts. Two essential inquiry features, which involve the *formulation of explanations from evidence* as well as *communication and justification of explanations*, are addressed by this principle.

Principle 7: Require Students during Class to Apply Their Acquired Knowledge or Skills in Solving Differentiated Tasks and Tackling Real-World Problems, Because Learning Should Be Meaningful to Them. According to the 5E inquiry model (Bybee, 2009), elaboration is an essential ingredient in the learning process. In an inquiry-based flipped classroom scenario, students should have the opportunity to apply what they have already learned in-class supported by teachers. Especially, engaging students in tackling problems found in the real world can promote student learning (Tawfik & Lilly, 2015). Through providing differentiated tasks, the needs of different students can be respected.

Principle 8: Implement Small-Group Learning Activities during Class to Facilitate Peer-Assisted Learning. In flipped classroom scenarios, gained in-class time can be spent, inter alia, on small-group learning activities. According to social constructivism (Vygotsky, 1978), learning among a group is important for constructing knowledge. Concerning inquiry-based flipped classroom scenarios, implementing small-group activities during exploration, explanation and elaboration could be fruitful because of peer-assisted learning. Through peer interactions, learners can work together on answering the questions to be investigated, discuss their findings or applying their acquired knowledge to varied tasks jointly.

Conclusion, Limitations and Further Research

The design-based research study presented in this paper had a twofold purpose: (1) develop a useful design heuristic for lesson planning of 5E-based flipped classroom scenarios and (2) contribute to theory with design principles for fostering learning through inquiry in flipped classroom scenarios. Over 2 years within two design-based research cycles, the design heuristic as well as the underpinning design principles evolved. For the development of the design heuristic, we opted for a document analysis of lesson plans from our online course. We used the 5E lesson plan scoring instrument (Goldston et al., 2013) to analyse these lesson plans. During the lesson plan analysis, we detected strengths as well as weaknesses of the design heuristic and revised it accordingly. Analysis with the 5E ILPv2 showed the design heuristic could assist teachers' lesson planning practice to a certain extent. The collected lesson plans were in both design research cycles mainly in line with the 5E model. However, teachers did not address the phase of evaluation satisfactorily, an issue which could not be resolved in this design-based research study. How to support teachers in assessing learning through inquiry in flipped classroom scenarios could be examined in further research.

As flipped classroom approaches, as well as the 5E inquiry model (Bybee, 2009), are widely used in STEM education, the proposed design heuristic is not domain specific. Even if we have developed the design heuristic with mathematics teachers, further research could examine the use of the design heuristic for lesson planning interdisciplinary or among other STEM subjects. Prior studies (e.g. Aşıksoy & Ozdamli, 2017) have already investigated inquiry-based learning in a flipped classroom scenario in STEM disciplines individually with promising results. Hence, in the future inquiry-based flipped classroom approaches like the 5E-based flipped classroom could be one of the emerging pedagogies for STEM education.

We are aware that we did not explicitly mention students' misconceptions in the design heuristic since they are implicitly given. For example, in the phase of explanation, teachers may come across students' misconceptions when supporting learners in linking their explanations to relevant concepts or theories. Based on the subject, teachers may have to use different strategies to tackle these misconceptions. There are other domain-specific design heuristics (e.g. Janssen et al., 2009) particularly focusing on appropriately addressing learners' misconceptions as it could foster deeper learning. Admittedly, we would recommend asking teachers to state possible students' misconceptions based on the lesson objectives before using the design heuristic presented in this paper.

The developed design principles for inquiry-based flipped classroom scenarios were developed in a specific context and cannot be generalised yet. For generalisation, the proposed design principles must be validated in different contexts in further research (Plomp, 2013). Nevertheless, we believe that the presented design principles constitute a valuable contribution to the existing knowledge regarding fostering learning through inquiry in flipped classroom scenarios. Taken the design principles and the design heuristic together, they should complement each other. On the one hand, the design heuristic can assist educators in arranging in-class as well as out-of-class activities in flipped classroom sequences to enhance inquiry-based learning. On the other hand, the design principles contribute to theory and offer educators more insights in selecting activities.

Acknowledgements The Austrian University College of Virtual Teacher Education supported the study reported in this paper by providing a platform to carry out our online professional development course, the quality assurance of the course and the second scorer for data analysis.

Author Contribution This authorship contribution statement follows the CRedit contributor role taxonomy (Brand, Allen, Altman, Hlava, & Scott, 2015).

SS: project administration, conceptualization, methodology, investigation, formal analysis, writing—original draft, writing—review and editing. ZL: conceptualization, methodology, writing—review & editing. EV: conceptualization, methodology, writing—review and editing.

Funding Open access funding provided by Johannes Kepler University Linz.

References

Abeysekera, L., & Dawson, P. (2015). Motivation and cognitive load in the flipped classroom: Definition, rationale and a call for research. *Higher Education Research & Development, 34*(1), 1–14. https://doi.org/10.1080/07294360.2014.934336.

Amiel, T., & Reeves, T. C. (2008). Design-based research and educational technology: Rethinking technology and the research agenda. *Educational Technology & Society, 11*(4), 29–40. Retrieved from www.jstor.org/stable/jeductechsoci.11.4.29.

Aşıksoy, G., & Ozdamli, F. (2017). The flipped classroom approach based on the 5E learning cycle model - 5ELFA. *Croatian Journal of Education, 19*(4), 1131–1166. https://doi.org/10.15516/cje.v19i4.2564.

Bakker, A. (2018). *Design research in education: A practical guide for early career researchers*. New York, NY: Routledge. Retrieved from https://www.taylorfrancis.com/books/9781351329422.

Bilgin, I., Coşkun, H., & Aktaş, I. (2013). The effect of 5E learning cycle on mental ability of elementary students. *Journal of Baltic Science Education, 12*(5), 592–607.

Borko, H., & Putnam, R. T. (1996). Learning to teach. In D. C. Berliner & R. C. Calfee (Eds.), *Handbook of educational psychology* (pp. 673–708). New York: MacMillan.

Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal, 9*(2), 27–40. https://doi.org/10.3316/QRJ0902027.

Brand, A., Allen, L., Altman, M., Hlava, M., & Scott, J. (2015). Beyond authorship: Attribution, contribution, collaboration, and credit. *Learned Publishing, 28*(2), 151–155. https://doi.org/10.1087/20150211.

Bybee, R. W. (2009). *The BSCS 5E instructional model and 21st century skills*. Colorado Springs, CO: BSCS.

Bybee, R. W., Taylor, J. A., Gardner, A., van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). The BSCS 5E instructional model: Origins and effectiveness. *Colorado Springs, CO: BSCS, 5*, 88–98.

Cevikbas, M., & Kaiser, G. (2020). Flipped classroom as a reform-oriented approach to teaching mathematics. *ZDM*, 1–15. https://doi.org/10.1007/s11858-020-01191-5.

Charles-Ogan, G., & Williams, C. (2015). Flipped classroom versus a conventional classroom in the learning of mathematics. *British Journal of Education, 3*(6), 71–77.

Cheng, L., Ritzhaupt, A. D., & Antonenko, P. (2019). Effects of the flipped classroom instructional strategy on students' learning outcomes: A meta-analysis. *Educational Technology Research and Development, 67*(4), 793–824. https://doi.org/10.1007/s11423-018-9633-7.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9–13. https://doi.org/10.3102/0013189X032001009.

Correia, C. F., & Harrison, C. (2019). Teachers' beliefs about inquiry-based learning and its impact on formative assessment practice. *Research in Science & Technological Education, 25*(1), 1–22. https://doi.org/10.1080/02635143.2019.1634040.

De Araujo, Z., Otten, S., & Birisci, S. (2017). Conceptualizing "homework" in flipped mathematics classes. *Educational Technology & Society, 20*(1), 248–260. Retrieved from www.jstor.org/stable/jeductechsoci.20.1.248.

Duran, L. B. (2003). Investigating brine shrimp. *Science Activities: Classroom Projects and Curriculum Ideas, 40*(2), 30–34. https://doi.org/10.1080/00368120309601119.

Fredriksen, H. (2020). Exploring realistic mathematics education in a flipped classroom context at the tertiary level. *International Journal of Science and Mathematics Education. Advance online publication., 19*, 377–396. https://doi.org/10.1007/s10763-020-10053-1.

Goldston, M. J., Dantzler, J., Day, J., & Webb, B. (2013). A psychometric approach to the development of a 5E lesson plan scoring instrument for inquiry-based teaching. *Journal of Science Teacher Education, 24*(3), 527–551. https://doi.org/10.1007/s10972-012-9327-7.

Goos, M. (2004). Learning mathematics in a classroom community of inquiry. *Journal for Research in Mathematics Education, 35*(4), 258–291. https://doi.org/10.2307/30034810.

Harrison, C. (2014). Assessment of inquiry skills in the SAILS project. *Science Education International, 25*(1), 112–122.

Hillmayr, D., Ziernwald, L., Reinhold, F., Hofer, S. I., & Reiss, K. M. (2020). The potential of digital tools to enhance mathematics and science learning in secondary schools: A context-specific meta-analysis. *Computers & Education, 153*, advance online publication. https://doi.org/10.1016/j.compedu.2020.103897.

Jang, H. (2016). Identifying 21st century STEM competencies using workplace data. *Journal of Science Education and Technology, 25*(2), 284–301. https://doi.org/10.1007/s10956-015-9593-1.

Janssen, F. J. J. M., Tigelaar, D. E. H., & Verloop, N. (2009). Developing biology lessons aimed at teaching for understanding: A domain-specific heuristic for student teachers. *Journal of Science Teacher Education, 20*(1), 1–20. https://doi.org/10.1007/s10972-008-9118-3.

Jensen, J. L., Kummer, T. A., & Godoy, P. D. d. M. (2015). Improvements from a flipped classroom may simply be the fruits of active learning. *CBE Life Sciences Education, 14*(1), 1–12. https://doi.org/10.1187/cbe.14-08-0129.

Kapur, M. (2010). Productive failure in mathematical problem solving. *Instructional Science, 38*(6), 523–550. https://doi.org/10.1007/s11251-009-9093-x.

Kerrigan, J. (2018). *Productive failure in the flipped mathematics classroom* (dissertation). Rutgers, The State University of New Jersey, New Jersey. https://doi.org/10.7282/T3QV3QX5.

Kim, M. K., Kim, S. M., Khera, O., & Getman, J. (2014). The experience of three flipped classrooms in an urban university: An exploration of design principles. *The Internet and Higher Education, 22*, 37–50. https://doi.org/10.1016/j.iheduc.2014.04.003.

Kondracki, N. L., Wellman, N. S., & Amundson, D. R. (2002). Content analysis: Review of methods and their applications in nutrition education. *Journal of Nutrition Education and Behavior, 34*(4), 224–230. https://doi.org/10.1016/S1499-4046(06)60097-3.

Lo, C. K. (2017). Toward a flipped classroom instructional model for history education: A call for research. *International Journal of Culture and History (EJournal), 3*(1), 36–43. https://doi.org/10.18178/ijch.2017.3.1.075.

Lo, C. K. (2018). Grounding the flipped classroom approach in the foundations of educational technology. *Educational Technology Research and Development, 66*(3), 793–811. https://doi.org/10.1007/s11423-018-9578-x.

Lo, C. K., & Hew, K. F. (2017). A critical review of flipped classroom challenges in K-12 education: Possible solutions and recommendations for future research. *Research and Practice in Technology Enhanced Learning, 12*(1), 4. https://doi.org/10.1186/s41039-016-0044-2.

Lo, C. K., Hew, K. F., & Chen, G. (2017). Toward a set of design principles for mathematics flipped classrooms: A synthesis of research in mathematics education. *Educational Research Review, 22*, 50–73. https://doi.org/10.1016/j.edurev.2017.08.002.

Love, B., Hodge, A., Corritore, C., & Ernst, D. C. (2015). Inquiry-based learning and the flipped classroom model. *PRIMUS, 25*(8), 745–762. https://doi.org/10.1080/10511970.2015.1046005.

National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. National Academies Press.

Omotayo, S. A., & Adeleke, J. O. (2017). The 5E instructional model: A constructivist approach for enhancing students' learning outcomes in mathematics. *Journal of the International Society for Teacher Education, 21*(2), 15–26 Retrieved from https://eric.ed.gov/?id=EJ1176946.

Otten, S., de Araujo, Z. & Sherman, M. (2018). Capturing variability in flipped mathematics instruction. *Proceedings of the 40th Annual Meeting of the North American Chapter of the International Group for the Psychology of Mathematics Education.*, 1052–1059. Retrieved from http://par.nsf.gov/biblio/10097331.

Plomp, T. (2013). Educational design research: An introduction. In P. Tjeerd & N. Nienke (Eds.), *Educational design research. Part a: An introduction* (pp. 10–51). SLO: Enschede, The Netherlands.

Ruiz-Primo, M. A., & Furtak, E. M. (2007). Exploring teachers' informal formative assessment practices and students' understanding in the context of scientific inquiry. *Journal of Research in Science Teaching, 44*(1), 57–84. https://doi.org/10.1002/tea.20163.

Schallert, S., Lavicza, Z., & Vandervieren, E. (2020). Merging flipped classroom approaches with the 5E inquiry model: a design heuristic. *International Journal of Mathematical Education in Science and Technology*, advance online publication. https://doi.org/10.1080/0020739X.2020.1831092.

Sezer, B. (2017). The effectiveness of a technology-enhanced flipped science classroom. *Journal of Educational Computing Research, 55*(4), 471–494. https://doi.org/10.1177/0735633116671325.

Song, Y., & Kapur, M. (2017). How to flip the classroom – "Productive failure or traditional flipped classroom" pedagogical design? *Educational Technology & Society, 20*(1), 292–305 Retrieved from http://www.jstor.org/stable/jeductechsoci.20.1.292.

Tawfik, A. A., & Lilly, C. (2015). Using a flipped classroom approach to support problem-based learning. *Technology, Knowledge and Learning, 20*(3), 299–315. https://doi.org/10.1007/s10758-015-9262-8.

The Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher, 32*(1), 5–8. https://doi.org/10.3102/0013189X032001005.

Tuan, H.-L., Yu, C.-C., & Chin, C.-C. (2017). Investigating the influence of a mixed face-to-face and website professional development course on the inquiry-based conceptions of high school science and mathematics teachers. *International Journal of Science and Mathematics Education, 15*(8), 1385–1401. https://doi.org/10.1007/s10763-016-9747-5.

Tuna, A., & Kacar, A. (2013). The effect of 5E learning cycle model in teaching trigonometry on students' academic achievement and the permanence of their knowledge. *International Journal on New Trends in Education and Their Implications, 4*(1).

Van den Akker, J. (2013). Curricular development research as specimen of educational design research. In P. Tjeerd & N. Nienke (Eds.), *Educational design research. Part a: An introduction* (pp. 53–70). SLO: Enschede, The Netherlands.

Voigt, M., Fredriksen, H., & Rasmussen, C. (2020). Leveraging the design heuristics of realistic mathematics education and culturally responsive pedagogy to create a richer flipped classroom calculus curriculum. *ZDM. Advance online publication, 52*, 1051–1062. https://doi.org/10.1007/s11858-019-01124-x.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Wang, F., & Hannafin, M. J. (2005). Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development, 53*(4), 5–23. https://doi.org/10.1007/BF02504682.

Wasserman, N. H., Quint, C., Norris, S. A., & Carr, T. (2015). Exploring flipped classroom instruction in Calculus III. *International Journal of Science and Mathematics Education, 15*(3), 545–568. https://doi.org/10.1007/s10763-015-9704-8.

Wei, X., Cheng, I.-L., Chen, N.-S., Yang, X., Liu, Y., Dong, Y., et al. (2020). Effect of the flipped classroom on the mathematics performance of middle school students. *Educational Technology Research and Development, 68*, 1461–1484. https://doi.org/10.1007/s11423-020-09752-x.

Weinhandl, R., & Lavicza, Z. (2018). Introducing teachers to a technology-supported flipped mathematics classroom teaching approach. In H.-G. Weigand, A. Clark-Wilson, A. Donevska-Todorova, E. Faggiano, N. Grønbæk, & J. Trgalova (Eds.), *Proceedings of the Fifth ERME Topic Conference (ETC 5) on Mathematics Education in the Digital Age (MEDA)* (pp. 289–296). Copenhagen, Denmark: University of Copenhagen.

Weinhandl, R., & Lavicza, Z. (2019). Exploring essential aspects when technology-enhanced flipped classroom approaches are at the heart of professional mathematics teacher development courses. *International Journal for Technology in Mathematics Education, 26*(3), 139–143.
Weinhandl, R., Lavicza, Z., & Houghton, T. (2020). Mathematics and STEM teacher development for flipped education. *Journal of Research in Innovative Teaching & Learning*, advance online publication.
Zheng, L., Bhagat, K. K., Zhen, Y., & Zhang, X. (2020). The effectiveness of the flipped classroom on students' learning achievement and learning motivation: A meta-analysis. *Educational Technology & Society, 23*(1), 1–15.

Affiliations

Stefanie Schallert[1] · Zsolt Lavicza[1] · Ellen Vandervieren[2]

Zsolt Lavicza
lavicza@gmail.com

Ellen Vandervieren
ellen.vandervieren@uantwerpen.be

[1] Department of STEM Education, Johannes Kepler University Linz, Altenberger Straße 54, 4040 Linz, Austria

[2] School of Education, University of Antwerp, Venusstraat 35, 2000 Antwerp, Belgium