Cultivating a Design Thinking Mindset in Educationally Disadvantaged Students Using a Design-based Activity

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Abstract

Science, technology, engineering, and mathematics (STEM) education, as an educational policy, provides opportunities for students to learn these disciplines in more integrated ways than traditional methods. This can be pedagogically accomplished via a design-based approach where students engage collaboratively in solving engineering problems using various domains of knowledge and skills. In this pedagogical process, design thinking is vital. However, little is known about whether students develop this kind of thinking and its mindset when engaging in design-based activities. The purpose of this study is to examine the influence of a design-based activity on design thinking. Participants included 18 ninth-grade students in a small rural school. The data were collected using a Likert-scale questionnaire before and after the design-based activity, in combination with classroom observations and focus group interviews with the students. The Wilcoxon signed-rank test was used to analyse the quantitative data and a thematic analysis method was utilised for the qualitative data. The results indicate that the students were significantly more comfortable with solving engineering problems, even though other aspects of design thinking mindset (e.g., user empathy, collaboratively working with diversity, orientation toward learning, and creative confidence) were not significantly different. These results are discussed based on the enacted nature of the activity.

Introduction

Science, technology, engineering, and mathematics (STEM) education has been recognised as a reform movement in education with the aim to enhance economic competitiveness by increasing a workforce in STEM, which are fundamental disciplines for creating innovations in global markets (Promboon, Finley, & Kaweekijmanee, 2018). While STEM education can be interpreted differently among scholars, one interpretation is that 'two or more of the discipline areas being applied in tandem, and drawing upon the 21st century competencies, to solve problems or create products' (Sheffield, Blackley, Koul, & Yeung, 2018, p. 1). With a focus on solving problems and creating products, the nature of STEM in educational contexts can be reflected by the nature of engineering (Quinn, Reid, & Gardner, 2020). In other words, engineering is considered not only as the discipline most relevant to students' everyday experiences, but also the discipline that connects the other three disciplines together. As a consequence, the engineering design process is pedagogically recommended as a key approach to integrated STEM education (Kelly & Knowles, 2016).

Inherent in any design-based approach is design thinking (DT) that operates when individuals engage in an engineering design process. As a mode of thinking (Li et al., 2019), DT can generally be defined as 'an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign' (Razzouk & Shute, 2012, p. 330). It may also refer to an ability to combine empathy, creativity, and rationality to analyse and fit solutions to particular problems (Wrigley & Straker, 2015), as engineers aim to solve the problems of others, not their own (Dym, Agogino, Eris, Frey, & Leifer, 2005). Including its affective dimension, DT can be described using terms such as 'traits' (Blizzard et al., 2015), 'attributes' (Schweitzer, Groeger, & Sobel, 2016), 'dispositions' (Koh, Chai, Wong, & Hong, 2015), 'tenets' (Marks & Chase, 2019), and 'mindsets' (Dosi, Rosati, & Vignoli, 2018). Regardless of the terms, DT fosters students' meaningful learning of STEM within the context of design-based approaches (Cook & Bush, 2018).

Li et al. (2019) made the argument that 'everyone designs and can design' (p. 94); thus, DT is vital for all students. However, that everyone designs and can design does not mean that everybody is born with the sophisticated ability of DT. Several studies have demonstrated the differences between novice and expert designers. For example, Mentzer, Becker, and Sutton (2015) have observed that novice designers engage in DT with little understanding of the problem from clients' perspectives and that they tend to become fixed on a single solution rather than comparing alternatives. In a similar vein, Crismond (2013) has noted some so-called misconceptions of design practices commonly found among novice designers, as compared to expert designers. For example, novice designers are likely to treat design challenges as well-defined problems and be reluctant to generate more than one solution. Nonetheless, what is implied in such comparisons between novice and expert designers is that DT is something teachable and learnable.

Despite that DT facilitates students meaningfully learning STEM via design-based approaches (Cook & Bush, 2018) and that DT 'is important for every student to develop and have in the twenty-first century' (Li et al., 2019, p. 94), little is known about whether and in what respect experiences in design-based activities would cultivate students' DT. Thus, there is a need for research to investigate how students experience engineering design as a pedagogical approach (Kelley & Sung, 2017), which can in turn provide insight into how a design-based activity can be shaped to better promote students' DT (Mentzer et al., 2015). This study aims to examine DT among a group of lower secondary students before and after engaging in a design-based activity. In doing so, two research questions were posed: (1) Do students develop DT after engaging in a design-based activity and in what respect? and (2) What kind of experiences during the design-based activity influence students' DT? Given various aspects of DT among scholars, what in particular DT means in the context of this study, is operationally articulated in what follows.

Design Thinking

According to Mentzer (2014), DT is 'an elusive and difficult construct to define' (p. 53), as it entails various aspects. Consequently, different scholars may describe DT differently. Some may describe DT cognitively as a mode of thinking (e.g., analytical and creative thinking) employed in the process of designing (Li et al., 2019), whereas others may describe DT methodologically as a process (e.g., defining the problem, modelling ideas, and making prototypes) when engaging in a design-based activity (Sung & Kelly, 2019). Additionally, DT can be described affectively as a mindset (e.g., being optimistic, collaborative, and human-centered) operating during the process of designing (Gudipati & Sethi, 2017). Given its multi-faceted nature, Goldman and Kabayadondo (2017) define DT as 'a method of problem-solving that relies on a complex of skills, processes, and mindsets that help people generate novel solutions to problems' (p. 3).

In educational contexts in which STEM education at K–12 levels is promoted pedagogically through the engineering design process, DT can also be conceptualised in different ways. On the one hand, DT is viewed as an instructional approach to facilitating particular learning outcomes among students. Based on a review regarding the integration of DT into K–12 curricula, Rusmann and Ejsing-Duun (2021) conclude that ‘design thinking as a teaching method has the potential to improve students’ learning’ (p. 22) and ‘design thinking also nurtures the competences that are commonly believed to be necessary for all 21st-century students such as collaboration, communication, metacognition, and critical thinking’ (p. 23). Thus, DT in this sense is similar to design-based instruction itself. According to Koh et al. (2015), this view is dominant in research promoting DT in K–12 education.

On the other hand, DT can be viewed as a learning outcome resulting from design-based instruction. According to Goldman and Kabayadondo (2017), the aim of taking DT to schools should be to ‘move beyond merely going through the steps of the process and to develop mindset-change experiences such as empathy development, participation in team collaboration, commitment to action-oriented problem-solving, a sense of efficacy, and understanding that failure and persistence to try again after failures are necessary and productive aspects of success’ (p. 3). Seeing DT as a mindset underlying the process of designing, scholars foster and examine students’ DT as a learning outcome. For example, Goldman, Zielezinski, Vea, Bachas-Daunert, and Kabayadondo (2017) assessed the development of three affective aspects of DT among students (i.e., responding with empathy, engaging teamwork, and building confidence in creating solutions).

Scholars who approach DT affectively as a mindset have identified a lengthy list of aspects of DT (e.g., Cook & Bush, 2018; Dosi et al., 2018; Schweitzer et al., 2016). Based on these lists (see Supplementary Material for detail), it can be summarised that DT as a mindset entails empathy with people’s problems, a desire to take action, and learning during the process of problem solving in order to have an impact on people’s lives and societies. While designing, those with a DT approach wish to communicate ideas and collaborate with others, be open to diverse perspectives, be mindful to the process of problem solving, be aware of their own thinking modes, be comfortable with ambiguity and uncertainty, be confident in creativity, embrace risks when trying different approaches or testing new ideas, and be resilient not to back down from the challenging problems.

In Thailand, where this study was conducted, DT has gained increasing attention because of the STEM education policy. As Thai scholars, we also used Dosi et al.’s (2018) comprehensive list of aspects of DT to measure teachers’ and students’ perception of their DT (Ladachart, Ladachart, Phothong, & Suaklay, 2021; Ladachart, Cholsin, Kwanpet, Teerapanpong, Dessi, Phuangsuwan, & Phothong, 2021). While DT can be measured in several ways, measuring individuals’ perceptions of their own DT using Likert-type surveys can ‘provide insights about the extent they are able to think like designers’ (Koh et al., 2015, p. 115). In this regard, a similar set of DT aspects relevant in Thai contexts have been identified: (1) being comfortable with problems, (2) using empathy, (3) being mindful of the process, (4) collaboratively working with diversity, (5) being orientated to learning, and (6) having creative confidence.

To develop DT as a learning outcome, students are encouraged to engage in design-based activities. For example, Goldman et al. (2017) encouraged students to design structures in an amusement park for visitors (e.g., a roller coaster and a shelter to protect visitors from sunlight) to develop students’ DT mindset regarding empathy, collaboration, and creative confidence. In this regard, some scholars may expect not only that students develop DT but also that DT can facilitate other learning outcomes such as content knowledge and metacognition (Carroll, Goldman, Britos, Koh, Royalty, & Hornstein, 2010). Despite interventions occurring weekly for six months, Goldman et al. (2017) found that students' DT 'takes time to cultivate' (p. 92). This finding implies that engaging students in design-based activities is not sufficient for the development of a DT mindset. Specific scaffolding is required to cultivate DT mindsets among students (Koh et al., 2015).

There are examples of research indicating that specific scaffolding associated with some affective aspects of DT can help students engage in design-based activities productively. For example, Conlin, Chin, Blair, Cutumisu, and Schwartz (2015) included a brief discussion about the importance of seeking constructive criticism from stakeholders and about the importance of generating multiple prototypes before letting students engage in design-based activities. This scaffolding helped the students overcome their fear of failure. Marks and Chase (2019) introduced three tenets of DT, (1) 'make mistakes and learn from them', (2) 'go through cycles of make-test-think', and (3) 'try early and try often', as an intervention within design-based activities. This introduction encouraged iterative practice and a fail-forward mindset among students. Chusinkunawut, Henderson, Nugultham, Wannagatesiri, and Fakcharoenphol (2021) provided communicative scaffolding for students to engage in productive conversations within design-based activities.

Based on the literature review, it is inevitable that a DT mindset will become important for students in their future careers (Li et al., 2019). Students are expected to learn not only knowledge, skills, and attitudes in STEM disciplines but also to develop a DT mindset. However, while some research has suggested that engaging in design-based activities can improve their learning outcomes in STEM (Apedoe, Reynolds, Ellefson, & Schunn, 2008; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Kolodner et al., 2003), recent research has begun to demonstrate that development of a DT mindset in students is challenging (Koh et al., 2015). Moreover, research in this area with socioeconomically disadvantaged students is sparse. Given that cultivating students' DT mindset takes time (Goldman et al., 2017), design research is deemed appropriate, as it allows scholars to engage in an iterative process of designing, testing, and improving an intervention that aims to promote specific learning outcomes (Bakker, 2018).

Methodology

In this study, the notion of design research was adopted, as it seeks to involve iterative cycles of (1) preparation and design, (2) implementation, and (3) retrospective analysis of an educational intervention (Passarella, 2021). According to Bakker (2018), the purposes of design research are 'to develop theories about learning and the means that are designed to support that learning' (p. 18). In this design research, we specified two kinds of learning for socioeconomically disadvantaged Thai students: a conceptual understanding of torque and a DT mindset. Because the recent version of Thailand's Basic Education Core Curriculum (Bureau of Academic Affairs and Educational Standards, 2017) explicitly mandates teaching the scientific concept of torque but not DT, we prioritised the conceptual understanding of torque over a DT mindset in preparing and designing an instructional intervention. As reported elsewhere (Ladachart, Khamlarsai, & Phothong, 2022), the first cycle of this design research indicates a significant improvement in the students' scientific understanding of torque. Thus, this report aims to present a retrospective analysis of the instructional intervention, described below, which aimed to foster the students' DT mindset.

Bakker (2018) suggests that in conducting design research, 'researchers typically need to learn about several research approaches' (p. 7). Through the process of this design research, we utilised a mixed-methods approach to research to obtain both quantitative and qualitative data. This provides a better understanding of how the instructional intervention facilitates or inhibits a DT mindset and how it can be refined, than can be gained using one kind of data alone (Creswell & Plano Clark, 2011). Specifically, an embedded design of the mixed-methods approach was employed, in that the quantitative data were collected before and after the implementation of the instructional intervention within which the qualitative data were concurrently gathered. Therefore, the analysis of the qualitative data could provide a deeper explanation of the quantitative results. It is important to note that what is reported here is the initial result of the first cycle of this design research; further refinement of the instructional intervention is required to better scaffold a DT mindset among students. We assumed that some aspects of a DT mindset might not occur spontaneously as a by-product of engaging in design-based learning.

Context

This study took place in a secondary school located in a rural area in a northern province of Thailand. With a total of 100 students studying in the 7th to 12th grades, the school can be regarded as a small-sized school. The school has a total of 11 teachers, which included three science teachers. Of these three science teachers, only one teacher has a bachelor's degree in teaching physics; thus, she is responsible for teaching content associated with physics at almost all grade levels. It was this teacher (i.e., the second author) who voluntarily participated in this study, as she is pursuing a master's degree in curriculum and instruction at a university where the other two authors work. As schools in Thailand typically receive a budget according to the number of students, this school has continuously faced financial constraints, which results in a shortage of apparatus, equipment, and materials. Ultimately, these shortages affect the educational quality, which in turn gradually reduces the number of students in the school, as parents with sufficient income decide to send their children to larger schools in the cities that can offer a better quality of education. As a matter of fact, many students in the school are socio-economically disadvantaged in comparison with most students in the country.

Students

The only ninth-grade class in the school, which comprised 21 students, participated in this study, as they agreed to accept an invitation from their teacher to voluntarily engage in the design-based activity. These students included 13 males and eight females. At the time when this study began, they were about 14–15 years old. Based on a survey just before the design-based activity was implemented, 19 students indicated that they had seldom experienced the process of designing things, whereas the remaining two students revealed that they had never done it at all. Thus, it can be assumed that this study would offer these students an early experience in the process of engineering design to solve a problem of others. As three male students were absent on the day that the post-measurement was conducted, these three students were excluded from this study. Only the data from 18 students (10 males and eight females) were used for the purposes of this study. As previously noted, these students can be considered as educationally disadvantaged students, due to the low incomes of their families, which mainly do agricultural or labour work. Moreover, based on classroom observations, some of them had difficulty with mathematical calculations such as multiplication and division.

Activity

Among various models of the design-based approach to teaching and learning science, Apedoe et al.'s (2008) model of design-based learning was selected as a framework to develop the instructional activity. This model describes the engineering design process as a seven-stage cycle by which the students: (1) create designs, (2) evaluate outcomes, (3) generate reasons, (4) test ideas, (5) analyse results, (6) generalise the results, and (7) connect to big ideas. This model was chosen because it provides the students with an opportunity to use their prior knowledge and ideas to design initial products, before testing and reasoning why some of those products work better than others. This process can lead the students to meaningfully identify hypotheses about factors that might make some products work well, which can subsequently lead to scientific inquiries. As opposed to the nationally proposed model (STEM Education Thailand, 2014) in terms of which the students are mainly expected to have a scientific understanding before they are able to apply this understanding to solve an engineering problem, this model allows the students to construct a scientific understanding during an engineering design process. This instructional activity also included some characteristics that might also promote their DT mindset (see Supplementary Material for detail).

Data Collection

In this design research employing a mixed-methods approach, both quantitative and qualitative data were collected. A five-point Likert-type questionnaire was used to quantitatively measure the students' DT mindset before and after the design-based activity. As can be seen in the Supplementary Material, this questionnaire initially included 24 items, measuring six affective aspects of DT. These items resulted from a process of translating all 71 items in Dosi et al.'s (2018) questionnaire and validating them with two groups of Thai elementary teachers (Ladachart et al., 2021). Based on this process, only aspects comprising more than three items yielding a Cronbach's alpha higher than 0.70 were selected. This process was performed instead of an exploratory factor analysis, since we did not have access to a huge number of students during the COVID-19 pandemic. However, in calculating Cronbach's alpha for each aspect in the pre- and post-measurements, we found a negative value for an aspect in the pre-measurement. Thus, we excluded this aspect from the analysis. Thus, the questionnaire in use contained 21 items belonging to five aspects of DT mindset.

Qualitative data were gathered using focus group interviews with each group of students. The interviews were conducted by their teacher on a day when four students were absent. Thus, only 17 of the 21 students participated in the interviews. In each interview, the students were asked to describe the initial ideas among the group, what results the group gained from testing, how their ideas changed as a result of testing, how the group redesigned the table, whether the group achieved a better result, and how the group would explain their result. Moreover, the students were asked to express how they felt when designing tables to achieve the requirements specified by others, solving the problem with no certain solutions, working with group members assigned by the teacher, and what they had mostly learned from the design-based activity. Each interview lasted about six to nine minutes. In addition to conducting interviews, we recorded classroom observations using a video camera. Three of the five groups of students were randomly selected, and their verbal interactions were recorded during the design-based activity.

Data Analysis

Each type of data was analysed according to the relevant methods. For the quantitative data collected by the questionnaire, a descriptive method was used to calculate the means and standard deviations of the whole and each aspect of the DT mindset in both measurements.

Given that these data were ordinal and not normally distributed (based on a Shapiro-Wilk test, $p < .05$), we used a Wilcoxon signed-rank test at the significant value of .05 to determine whether the students' DT mindset after the design-based activity differed from their DT mindset before (Field, 2013). Using the software *JASP* (Goss-Sampson, 2020), we conducted this test both collectively for all five aspects and for each aspect of the DT mindset individually. Once we obtained tentative results for the quantitative analyses, we conducted a thematic analysis of the qualitative data collected in the focus group interviews and classroom observations to identify patterns that would explain what could make the students change or not change some aspects of their DT mindset after engaging in a design-based activity.

According to Clarke and Braun (2017), the thematic analysis is 'a method for identifying, analysing, and interpreting patterns of meaning ("themes") within qualitative data' (p. 297). It includes six phases, namely (1) familiarising oneself with data, (2) generating initial codes, (3) searching for themes, (4) reviewing potential themes, (5) defining and naming themes, and (6) producing the report (Braun & Clarke, 2012). In this study, we conducted the thematic analysis using a verbatim transcription of each interview and each group of students' verbal interactions, resulting in 320 textual pages. Then, we read and reread the textual transcription before the process of coding began. In coding, we were oriented toward a deductive approach based on the five aspects of a DT mindset (e.g., students were initially uncomfortable with achieving the design challenge). Once we completed the process of coding, we sought themes in light of the quantitative results (e.g., students relied on someone's idea in the group). We reviewed the potential themes, named them, and discussed them to examine any bias until we achieved a consensus. We collectively selected excerpts reflecting each theme to present the results.

Results

The descriptive analysis of the quantitative data indicates a collective pattern that the students initially had positive feelings about DT in terms of collaboratively working with diversity (4.24), orientation to learning (3.72), user empathy (3.65), and creative confidence (3.38), as these aspects yielded values greater than three (see Figure 1). However, they tended to be less positive with regard to being comfortable with problems (2.57). This is consistent with what they expressed in the survey, namely that they had never or rarely experienced the process of designing to solve problems. After having engaged in the design-based activity for about four weeks, however, these students tended to feel more comfortable with solving problems (2.91). Moreover, they tended to record slightly improved scores for the two aspects of user empathy (3.87) and orientation to learning (3.83). Compared to these improvements, the other two aspects of creative confidence (3.38) and collaboratively working with diversity (3.94) remained constant or even decreased slightly. Based on the Wilcoxon signed-rank tests, however, the only difference recorded that was statistically significant was regarding the aspect of being comfortable with problems, $z = 2.44$, $p = .02$, $r = 0.58$.

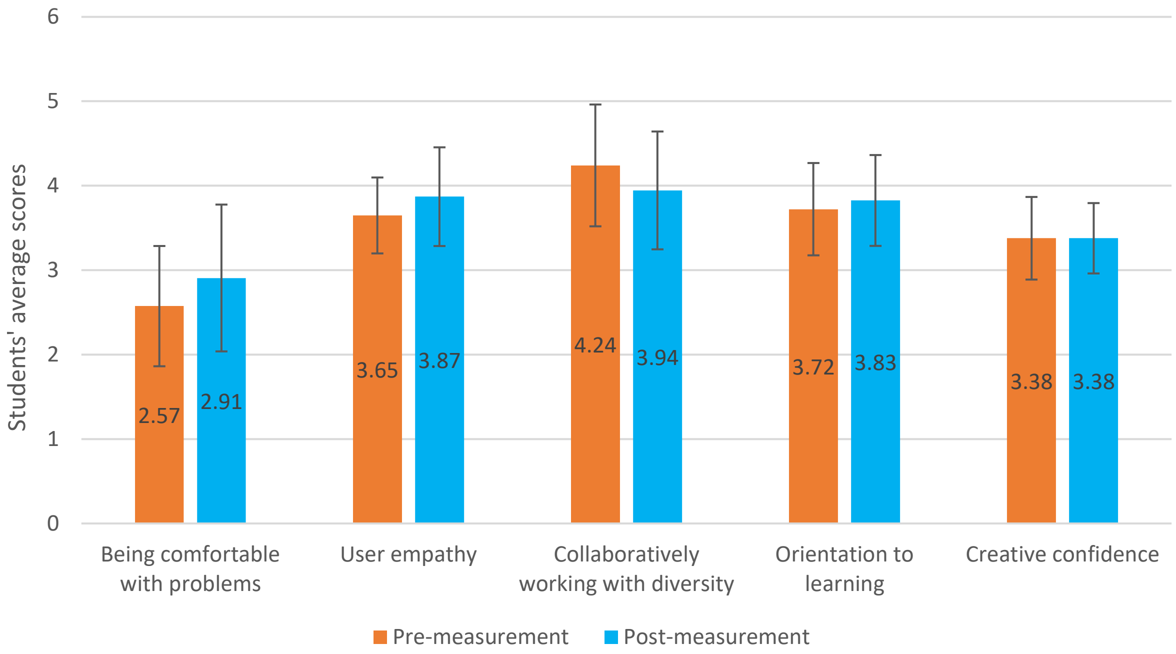

Figure 1. Students' design thinking mindset before and after the design-based activity.

Based on the thematic analysis of qualitative data (see Supplementary Material for detail), the first theme is that '*most students were initially uncomfortable with accomplishing the design challenge*'. As most students were uncertain about how to design the table, the second theme is that '*most groups relied mainly on the leading member's idea and decision*'. Since each group relied primarily on the leading student's idea, some of its members might not completely agree with it. Such disagreement could potentially cause a conflict within the group. Thus, the third theme is that '*the lack of collective decisions could lead to a potential conflict*'. However, with the reference from the highest achieving group and the teacher's scaffolding that focused on the concept of torque, each group was able to improve their prototype's performance to support more weight in the second round. Thus, the fourth theme is that '*with scaffolding, most students became more comfortable with solving the problem*'. Most students felt that they were better capable of managing uncertainty arising from the process of problem solving. Their comfort was evident during the design-based activity.

Discussion

This study aims to address two research questions, namely (1) whether a design-based activity develops the DT mindset of 18 educationally disadvantaged students and, if yes, (2) what kind of experiences during the design-based activity influence their DT mindset. In responding to the first research question, this study demonstrates that the design-based activity can significantly influence the students' DT mindset in only one aspect—that is, being comfortable with problems. Initially, most students were uncertain about whether and how they could accomplish the design challenge. They expressed such uncertainty not only through the questionnaire but also through their verbal interactions during the instructional activity and the focus group interviews. However, as the students engaged in the design-based activity, they were able to successfully overcome the design challenge. Their success might ultimately cause them to be more comfortable with solving unknown problems. This result highlights Martin-Hansen's suggestion (2018) that it is crucial that teachers 'encourage successful task completion' (p. 3) for students to meaningfully support their learning of STEM through design-based tasks.

As uncertainty is a defining feature of design-based tasks (Tracey & Hutchinson, 2016), it seems inevitable that the students would experience (and learn to manage) uncertainty during the design-based activity. In so doing, the students could use both internally focused strategies (e.g., developing confidence through practice and experience) and externally focused strategies (e.g., seeking additional information, collaboration, and feedback) (Tracey & Hutchinson, 2018). The qualitative data analysis confirms that the students used some of these strategies. For example, a boy mentioned during the focus group interviews that his group 'kept doing (it) and then got an idea', which indicates an internally focused strategy. The records of verbal interactions within the students' groups also reveal that they used externally focused strategies as they shared uncertainty and provided supportive responses to their colleagues. Given that the instructional model used in this study highlights 'public dialogue' (Apedoe et al., 2008) in which the students worked in a collaborative rather than competitive manner, it is also likely that peer interactions facilitated the students' management of their uncertainty (Jordan & McDaniel, 2014).

Given that the design-based activity does not significantly facilitate the development of the other four aspects of a DT mindset, this study is limited in providing insights into answers to the second research question. In a general sense, it supports Goldman et al. (2017), who claim that students' DT mindset 'takes time to cultivate' (p. 92). It also implies that a DT mindset should not be seen as a by-product of design-based learning; rather, it requires specific scaffolding to enable students to develop their DT mindsets (Koh et al., 2015). It is important to note that the instructional activity used in this study was designed to encourage the students to accomplish the design challenge using a contrasting-case strategy and scientific experimentation. Thus, it is reasonable that the students overcame the challenge and, thereby, became more comfortable with solving wicked problems. However, in our first cycle of design research, with the primary focus on conceptual learning of a scientific concept, no intentional scaffolding was provided for the students to develop the other four aspects of a DT mindset.

It was evident that initial uncertainty during the design-based activity might have caused each group of students to rely primarily on the idea proposed by its leading member. Even when the leading member explicitly asked for contributions, the other members hesitated to propose ideas and make decisions. This way of working was problematic because each group was limited to working on one idea. It was even more problematic when the leading member proposed the idea without clarity (e.g., using a lot of pronouns without antecedents), so the other group members could not thoroughly understand it and were not able to evaluate its pros and cons. Without alternative ideas, each group was unlikely to make collective decisions regarding potential designs. At best, some groups used voting as a strategy to make collective decisions about their prototype. However, the strategy of voting may be ineffective if all members do not reflectively evaluate the pros and cons of the ideas. In their study with elementary students engaging in design-based activities, Wendell, Wright, and Paugh (2017) demonstrated that it is crucial to scaffold the students to engage in reflective and collaborative decision-making, which was absent in this study.

Relying primarily on the leading member's idea without truly collective decisions within the groups, can have unintentional negative consequences. Because some members of each group may not completely agree with the idea proposed by the leading member, though they may not explicitly challenge it, those members may not feel ownership of the working idea. As a result, they may engage less in the design-based activity. Moreover, as evident in this study, disagreement regarding possible designs and unequal opportunities to engage in the design-based activity can create conflicts among students. While such conflicts are common for professional designers, as some ideas are necessarily ‘killed off’ (Schweitzer et al., 2016, p. 77), students may not be familiar with conflict and may not know how to resolve conflicts effectively. Thus, they need specific scaffolding to learn how to collaboratively overcome conflicts. For example, Chusinkunawut et al. (2021) provided communicative scaffolding for students to discuss, negotiate, evaluate, and argue about potential ideas. However, this kind of scaffolding was absent in this study.

The design-based activity in this study did not enable the students to empathise with users to a significant degree. Based on a retrospective analysis of the design-based activity, it is evident that the role of users manifested only at the beginning, when the teacher introduced the students to the design challenge and its requirements and criteria. Once the requirements and criteria were set, the role of users was not explicitly mentioned either in the whole-class or the within-group discussions. Thus, it should not be surprising that the students were not better able to empathise with users’ needs. By contrast, in one of our studies (Ladachart et al., 2021), in which secondary students engaged in designing a bimetal thermostat to function as an electrical switch, students better appreciated the human-centred nature of design following the instructional activity. In that study, a team of teachers encouraged students to consider the user’s perspective. Students in this study also failed to develop the other two aspects of a DT mindset (i.e., orientation toward learning and creative confidence) because these aspects were not mentioned during the design-based activity.

Implications

Given its limited success in facilitating the students’ DT mindset, the first cycle of this design research provides more questions than answers regarding how to cultivate a DT mindset among students in K–12 education. However, it offers several implications. First, it suggests that a DT mindset should not be seen as a by-product of design-based experiences. Although students may develop an ability to manage uncertainty, which is a defining feature of design-based activities, it is unlikely that students will spontaneously develop a DT mindset as a result of design-based learning. Thus, if design-based activities are expected to facilitate a DT mindset as an affective learning outcome, it is necessary that scaffolding be intentionally integrated into design-based activities. With appropriate scaffolding, design-based learning can be used as a pedagogical approach to STEM education, in which students learn not only science or mathematics, but also a mode of thinking and mindset, which are essential for the engineering design process used to create technology or innovation.

Second, the integration of the contrasting-case strategy into design-based learning can provide a kind of scaffolding. It not only supports students in learning a scientific concept (Chase et al., 2019) but also helps them manage uncertainty during design-based learning. When students observe a prototype made by a high achieving group and compare it with their own, they can use the prototype as a reference to evaluate and redesign their own prototypes. Observing the high achieving group’s prototype and comparing it with their own can lead to productive discussion within the other groups. It can also foster confidence among the other groups that they are also able to accomplish the design challenge. It can relieve some groups’ excessive uncertainty about overcoming the design challenge. However, the contrasting-case strategy in design-based learning should be used in a collaborative atmosphere. Otherwise, this strategy may have a negative impact on students who fear failure and embarrassment in front of the class. The teacher plays a critical role in creating a collaborative atmosphere, instead of a competitive one, in the classroom.

Third, this study indicates that the process of developing a DT mindset may not proceed smoothly, as students can encounter conflicts when collaborating with colleagues during the design-based activity. Such conflicts may arise because students have different ideas regarding possible designs, experience difficulty in making collective decisions, and have unequal opportunities to become involved in the design-based activity. Thus, scaffolding that facilitates managing and overcoming such conflicts is necessary. For example, students should be scaffolded to learn that they should extend empathy not only to users but also to colleagues who engage in the engineering design process (Rusmann & Ejsing-Duun, 2021). They may also need scaffolding to propose and share ideas in concrete ways without hesitation or concerns about being embarrassed by colleagues. Moreover, they may need scaffolding to evaluate the pros and cons of each idea to make reflective and collective decisions regarding potential designs. Additionally, students' creativity and desire to iterate the process of designing, prototyping, and testing should be facilitated and acknowledged. These kinds of scaffolding may help students learn smoothly and effectively during the design-based activity.

Limitations

This study has limitations. First, it involves a small number of students in a Thai school who are educationally and socioeconomically disadvantaged. Thus, its results cannot be statistically generalised to other contexts. However, analytical generalisations can be made in design research (Bakker, 2018) if researchers consider characteristics of the design-based activity used in this study to be useful in their context. Second, as this study was conducted during the COVID-19 pandemic, when most Thai schools turned to online instruction, the questionnaire measuring the students' DT mindset was not fully validated using factor analysis before the collection of quantitative data. Thus, one aspect of a DT mindset (i.e., mindfulness of the process) was excluded from this study. Moreover, our direct access to the students during the design-based activity was limited, so we were unable to gain more detailed qualitative data. However, with available data, it is possible to obtain useful insights into the benefits and the difficulties that students may gain and experience during design-based learning, leading to refinement of the design-based activity to better develop their DT mindset.

Future Work

Based on the results of the first cycle of design research, we want to provide several kinds of scaffolding in the design-based activity. First, as students have difficulty sharing and making collective decisions during the design-based activity, it may be useful to have individual students write and draw their own ideas. With such drawings, students can share ideas in a concrete way when entering into groups. Once each student has an opportunity to share their own idea, each group can reflectively evaluate the pros and cons of each idea, leading them to making collective decisions regarding potential designs. We have decided to refine the design-based activity in this way because we believe that an unequal opportunity to propose ideas and make collective decisions within each group of students, is the main cause of conflicts and causes some group members to be less involved in the design-based activity. Therefore, this kind of scaffolding may help reduce such conflicts. Providing a rubric explicitly listing criteria for each group of students to evaluate each idea may also facilitate more reflective and better decision-making (Wendell et al., 2017).

In this study, we provided a limited set of materials for each group of students to create a single prototype. We did so because we initially thought the limitation of materials could be used when discussing the nature of engineering with students to show that engineers design products with specifications, constraints, and goals. However, we have learned that providing too limited materials has a pitfall in that each group of students can create only one prototype. Thus, each group lacked an opportunity to compare several prototypes. Conlin et al. (2015) show that encouraging students to create and test multiple prototypes can help them accept negative feedback and learn from failure. By contrast, letting students create only one prototype can force them to try to make it perfect, causing them to spend most of the time creating the prototype rather than testing and improving it. Marks and Chase (2019) demonstrate that when students test a prototype early, they can better accomplish a design challenge and react more positively to failure than when they test the prototype later. Thus, the second scaffolding strategy is to provide students in each group opportunities to create multiple prototypes and test those prototypes early.

To implement the first and second scaffolding strategies in a practical way, we are looking for free software that would allow students to share and informally test their ideas in a more concrete and quicker way than using real materials and equipment. In doing so, we consider *Algodoo* promising. According to Gregorcic and Bodin (2017), *Algodoo* is a digital sandbox in which students can freely create a simulation, explore its effects, and solve physics problems. In this environment, students can create virtual tables with specifications according to the design challenge set by users' requirements. Then, they can test each virtual table to determine whether it can withstand accidental kicks and how much weight it can support at its edges. With this tool, each group of students can evaluate the pros and cons of each idea and reach collective decisions based on evidence gained from the virtual simulations. Based on their collective decisions, each group of students can choose the most promising ideas to physically create and empirically test a prototype.

Despite the significant improvement in students' ability to manage uncertainty arising during the design-based activity, their level of comfort with solving unknown problems after the design-based activity is still lower than the other aspects of a DT mindset. This result means that there is scope to improve this aspect of the DT mindset. Because uncertainty arises as students worry that their ideas may fail when they test them empirically, students need specific scaffolding to help them to consider failure positively. Research demonstrates that integrating a brief discussion regarding some aspects of a DT mindset such as the acceptance of critical feedback (Conlin et al., 2015) and learning from mistakes (Marks & Chase, 2019) before letting students engage in the engineering design process can significantly improve students' DT mindset. These studies highlight a need to make a DT mindset explicit. Thus, the third scaffolding strategy we intend to add in the next cycle of our design research is to explicitly discuss with students the usefulness of mistakes and failure. With these scaffolding strategies, we hope to achieve the design principles of design-based activities to better develop students' DT mindset.

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