SUPPLEMENTARY MATERIAL

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Aspects of design thinking mindset

Dosi et al. (2018)	Schweitzer et al. (2016)	Cook and Bush (2018)	Ladachart et al. (2021)	This study
1. tolerance for ambiguity 2. embracing risk 3. human centredness 4. empathy 5. mindfulness of process 6. holistic view 7. problem framing 8. team working 9. multi-disciplinary collaboration 10. being open to different perspectives 11. orientation to learning 12. Experimentation 13. bias toward action 14. critical questioning 15. abductive thinking 16. envisioning new things 17. creative confidence 18. desire to make a difference 19. optimism to have an impact	1. empathetic toward people’s needs and contexts 2. collaboratively geared and embracing diversity 3. inquisitive and open to new perspectives and learning 4. mindful of process and thinking modes 5. experientially intelligent 6. taking action deliberately and overtly 7. consciously creative 8. accepting of uncertainty and open to risk 9. modelling behaviours 10. having a desire and determination to make a difference 11. critically questioning	1. human-centredness 2. bias toward action 3. radical collaboration 4. culture of prototyping 5. mindfulness of process	1. being comfortable with uncertainty and risks 2. human-centeredness 3. mindfulness to the process and impacts on others 4. collaboratively working with diversity 5. orientation to learning by making and testing 6. being confident and optimistic to use creativity	1. being comfortable with problems 2. using empathy 3. collaboratively working with diversity 4. being orientated to learning 5. having creative confidence

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Detail of the design-based activity

The activity began by introducing the students to a problem using a video on *YouTube* and a post on the internet. The problem is that any person can accidentally kick an ordinary table's legs when they walk close to it. While this accident can be viewed as improvidence on the part of people, it can also be seen as problematic from the perspective of the table's designers, since Norman (2013) wrote that 'it is the duty of machines and those who design them to understand people. It is not our [users'] duty to understand the arbitrary, meaningless dictates of machines' (p. 6). Thus, this problem was discussed to make the point that an ordinary table can be redesigned to prevent such accidents, for example, by moving its legs inward. Then, the students were given a demonstration that such prevention can be achieved at the expense of less ability to support weight at the corners. After discussing the pros and cons of tables, the students were divided into five groups and told to design a new table with specific requirements of height, width, length, and movability, using a set of materials and equipment, which included a piece of corrugated plastic, eight wooden sticks, a roll of self-fusing tape, a ruler, a cutter, 10 pieces of 25-gram weights, a human model, and eight iron nuts. A key requirement was that their designed table's legs should not accidently be kicked by the human model.

Following Apedoe et al.'s (2008) model, each group of students designed and prototyped a table using their prior knowledge and ideas, resulting in a variety of table designs. One difference among the table designs was how each group of students used the nuts. It is important to note that, while it was clear what the other materials and equipment should be used for (e.g., a piece of corrugated plastic for the tabletop and wooden sticks for the table's legs), with regard to the nuts this was less clear; thus, there were several ways in which the nuts could be used. As a result, each group placed the nuts differently on their tables (e.g., at the top end, at the bottom end, or at both ends of each leg). These differences resulted in variations in the tables' ability to support weight, which was tested by placing 25-gram weights, one by one, at each corner until the tables overturned. Given the results of testing, the whole class compared and discussed the differences among their table designs and reasoned why some could support more weight than others. Using the strategy of contrasting cases (Chase et al., 2019), some students were able to note that, when the nuts were placed on the centre of the tabletop, the table could support considerably more weight. This point highlighted that the position of the nuts might be an important factor, which deserved further inquiry.

Following a guiding question on whether and how the position of weight on an object (e.g., a table) might influence it to overturn or rotate, each group of students conducted a scientific inquiry to explore the factors that might influence a lever to balance horizontally or to incline in a direction. Due to the limited apparatus and equipment available in the school, a meter ruler hanging on a test-tube stand was used as a lever. Each group could either vary the amount of mass or change the position of the mass between the two ends of the lever to observe whether it balances or inclines. After the students analysed the results of this scientific inquiry, the scientific concept of torque was introduced and discussed using a simulation from PhET (University of Colorado, 2020). Moreover, some applications of the scientific concept were briefly presented, such as a nail clipper, a two-wheel trolley, a paper trimmer, and an ice tong. At the end of the activity, each group of students were challenged once again to design a new table, using the same set of materials and equipment and the same requirements to achieve a better result. This design-based activity lasted about four weeks, with three hours spent on it each week. It was evident that the students significantly improved their understanding of torque (Ladachart et al., 2022); it was not clear whether this design-based activity also influenced their design thinking mindset.

While we designed the instructional activity with a focus on developing the students' scientific understanding of torque, it included some characteristics that might also promote their design thinking mindset. First, the students were asked to solve a wicked problem using the engineering design process (Buchanan, 1992). Thus, the design-based activity could provide them with an opportunity to experience and manage uncertainty arising during the process of problem solving (Jordan & McDaniel, 2014). With this opportunity, the students were likely to become more comfortable with solving unknown problems. Second, as the design-based activity focused on solving a human problem under conditions specified by users, the students were likely to empathise with users' needs and appreciate the human-centred nature of design (Zoltowski, Oakes, & Cardella, 2012). Third, while engaging in the design-based activities in which several factors simultaneously came into play, it was likely that the students were mindfully monitoring the process of designing (Tas, Aksoy, & Cengiz, 2019). Finally, as the students worked together to design and create prototypes of a new product, it was reasonable to expect that they might appreciate the value of materially mediated learning (Kangas, Seitamaa-Hakkarainen, & Hakkrainen, 2013), the benefits of collaboration (McLean, Nation, Spina, Susko, Harlow, & Bianchini, 2020) and the use of creativity (Doppelt, 2009).

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Detail of the questionnaire

Aspects of design thinking mindset	Items	Cronbach's alpha	
		Pre-test	Post-test
1. Being comfortable with problems	1.1. I am comfortable even in dealing with unsolved problems. 1.2. I enjoy it when the result of problem solving is unexpected. 1.3. I do not worry even when I do not know whether solving the problem has been successful.	0.75	0.82
2. User empathy	2.1. During the design process, I try to understand users' needs. 2.2. During the design process, I often see the problem from users' perspectives. 2.3. During the design process, I often put myself in users' shoes.	0.54	0.71
3. Mindfulness of the process	3.1. I am aware of when I must be open-minded and when I must focus on something. 3.2. I believe in discovering new things rather than worrying about failed results. 3.3. I am aware of when I need to redefine the problem more clearly.	-0.29	0.72
4. Collaboratively working with diversity	4.1. I like working in group rather than working alone. 4.2. I like working with people coming from different groups. 4.3. I accept the group's decisions even if I do not agree with them.	0.76	0.76
5. Orientation to learning	5.1. I often apply new things that I have learned. 5.2. I like learning from experiences, observations, and actions. 5.3. I like learning with colleagues within and across groups. 5.4. I like learning from people with diverse and different perspectives. 5.5. I like to get feedback and learn from it. 5.6. I try to get information that I did not know before. 5.7. I can discuss, share, and learn from mistakes.	0.78	0.82
6. Creative confidence	6.1. I can make inferences and propose ideas based on incomplete information. 6.2. I like to use creative thinking to solve complex problems. 6.3. I like to think of new things that are different from what exits. 6.4. I like to create a model to represent a new idea. 6.5. I like to create new conditions to test other possibilities.	0.62	0.54
Overall (before excluding the mindfulness of the process)		0.76	0.89
Overall (after excluding the mindfulness of the process)		0.73	0.86

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It is important to note that this study was conducted during the COVID-19 pandemic, which caused most schools in Thailand to change from normal instruction in classrooms to online instruction platforms to protect their students from the pandemic. Consequently, validating the questionnaire with students was not possible at that time. However, as the situation improved for a short period and some schools returned to onsite instruction, we were able to validate the questionnaire with 890 secondary students using factor analysis (Ladachart et al., 2021); their results confirmed a structure of a design thinking mindset similar to the structure we validated with the teachers. The only difference was that the items originally belonging to the factor 'empathy' in Dosi et al.'s (2018) list of design thinking mindset factors did not appear to constitute a single factor. Rather, they were merged with other related factors (e.g., human-centredness and mindfulness of the process), reflecting that 'empathy […] functions from the beginning to the end of a design project' (Hess & Fila, 2016, p. 108). Given that 'empathy [is the] most important piece of the design thinking process' (Cook & Bush, 2018, p. 99), we retained user empathy, whose meaning is similar to human-centredness, as a factor in this study.

Despite this limitation, the questionnaire yielded acceptable values of Cronbach's alpha of 0.76 and 0.89, respectively, in the pre- and post-measurements completed by the students in this study. However, in calculating Cronbach's alpha for each factor in the pre- and post-measurements, we found a negative value (−0.29) for the factor 'mindfulness of the process' in the pre-measurement. Carefully interpreting the items belonging to this factor, we found that item 3.2 tended to have a different meaning than the other two items. Moreover, item 3.3 correlated negatively with the scale. Removing any item did not improve the value of Cronbach's alpha for this factor. Consequently, while Cronbach's alpha of this factor in the post-measurement was acceptable (0.72), we excluded this factor from the analysis. Thus, the questionnaire in use contained 21 items belonging to five aspects of design thinking mindset. Its Cronbach's alpha in the pre- and post-measurements were 0.73 and 0.86, respectively. Although some factors (i.e., user empathy and creative confidence) produced values of Cronbach's alpha slightly lower than 0.70, these values may be lower because of the small number of students (Bonett, 2002).

Detail of qualitative results

Based on the thematic analysis of qualitative data collected from students' verbal interactions and focus group interviews, the first theme is that '*most students were initially uncomfortable with accomplishing the design challenge*'. They were uncertain whether they could achieve the design requirements under the given conditions (i.e., materials, equipment, and time). For example, once the teacher introduced the design challenge, a girl in Group 3 said that 'Will we survive?'. When a boy in this group asked his group members how to design the table's legs, the same girl expressed her frustration: 'I'm suddenly discouraged'. In a similar vein, Group 2 initially experienced uncertainty regarding how to design the table and, especially, how to use nuts in their design. The members of this group kept asking questions regarding 'how to use nuts', 'where to put nuts', and 'how to design the table' without anyone suggesting an answer. Such uncertainty was confirmed in the focus group interviews in which a girl stated, 'It is difficult to think', and a boy also commented, 'We could think of a design, but with the available material or equipment, we must think of another design'. Moreover, some students suggested that they required 'more time' to finish the 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*'. Two of the three groups whose verbal interactions were recorded followed this theme. For example, once challenged by the teacher, Group 1 was immediately dominated by a girl who urged her group members to cut the tabletop according to the requirement. Once they finished cutting the tabletop, another girl raised a question to the group about '*how to connect the base (the table's legs)'*. Then, the leading girl demonstrated her idea in an unclear way using pronouns without antecedents, as one of the following excerpts shows. It is not clear whether the other group members understood the leading girl's idea, despite her demonstration with materials, as they repeatedly raised the question of '*how*'. They accepted the leading girl's idea without evaluating its pros and cons. Moreover, the other group members proposed no alternative ideas. A similar incident also occurred in Group 2. While Group 3 asserted in the focus group interview that they used 'the majority' to make decisions regarding design, such decisions were forced by dichotomous questions raised by a boy, as another of the following excerpts shows.

Girl 1.1: Like this, isn't it? At first, do like this, right?
Girl 1.2: How?
Girl 1.1: Just like this. Or turn this down?
Girl 1.2: Like this?
Girl 1.1: Yes. I connected it. Stick it now.
Girl 1.2: How?
Girl 1.1: Stick here. Make it beautiful.

Boy 3.1: Oh! All are watching, not doing anything. Should the table's legs be wooden sticks or corrugated plastic?
Boy 3.2: Wooden.
Girl 3.1: Wooden.
Boy 3.1: How many (wooden sticks) for each leg?
Boy 3.2: Two for each.
Girl 3.2: It could also work if (the table's legs) are corrugated plastic.
Boy 3.1: Um. (I want to) take each one's idea. Should we use corrugated plastic or wooden sticks?

Since each group relied primarily on the leading student's idea, some of its members might not completely agree with it. Though they did not explicitly challenge 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*'. This theme is most apparent in Group 2, which was led and dominated by a girl. While a boy in this group seemed to have a different idea than the leading girl's, he was not allowed to share his idea. Consequently, he played with materials or equipment not in use (e.g., the human model and the audio recorder). The leading girl interpreted his actions as off-task. When the teacher visited this group to encourage collaboration, this boy expressed to the teacher that '*they both (two girls) do (it). They don't want friends to consult'*. As the leading girl subsequently struck with how to proceed her design, the boy asked, '*Do (it) if you still want to do. Otherwise, I will do (it)'*. While similar incidents were not apparent in the other two groups whose verbal interactions were recorded, the focus group interviews confirmed this theme, as a girl from another group, whose verbal interactions were not recorded, described what happened within her group:

> *'There was a bit of a quarrel the second time. One person* (who was absent on the day when the focus group interviews were conducted) *would like to do* (it) *differently from the first design to make it support more weight. It had too much detail* (with its eight legs whose top ends fixed together at the same point under the centre of the tabletop and the bottom ends spread out to make an octagon on the ground) *and time was catching up. No time for testing.'*

The design-based activity proceeded until all groups tested their prototypes in the front of the classroom. The teacher used the contrasting-case strategy (Chase et al., 2019) to encourage the students to observe the difference between the prototypes with high and low performance in supporting weight. Unfortunately, the highest achieving group's verbal interactions were not recorded. However, the focus group interview with this group reveals that by gradually moving the table's legs slightly inward and testing the result, this group was able to develop an idea to solve the problem. Specifically, a boy in this group said that his group *'just kept doing (it) and then got an idea'*. When they removed one of the table's legs and the table tended to tip over, they then put some nuts at the centre on the table's top to make it stay still. The video camera at the back of the classroom captured this moment, as the Figure below shows. This moment led this group to discover by chance that placing some nuts in that position could make the table capable of supporting more weight. Later, the teacher used this group's prototype to discuss and introduce the concept of torque to the students. This prototype became a reference for the other groups to improve their prototypes, as the following excerpt shows.

Figure. The moment a group discovered an idea to solve the problem.

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Girl 2.1:	They (students in the highest achieving group) used a lot of nuts.
Boy 2.1:	They used too many.
Girl 2.1:	They used them to make it (table) balance.
Boy 2.1:	They used resources excessively.
Girl 2.1:	For strength and balance.
Girl 2.2:	Guys, I would like to tell (you to) fix (the nuts) at the centre to make it balance.
Girl 2.1:	Plan to create the (table's) base by fixing (the nuts) at the bottom (of the tabletop) and the legs.

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*'. They 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. For example, a boy in Group 2, as he gradually became more involved with the girls, mentioned '*bright future*' to indicate confidence that his group would overcome the design challenge. In a similar vein, seeing the success of the highest achieving group, the leading boy in Group 3 encouraged his colleagues, who initially feared failure and embarrassment in front of their classmates, by saying, '*They can do (it), so we can do (it) too'*. Additionally, a boy in Group 1 gladly exclaimed, '*Yeah, it works!*' when his group's prototype achieved a satisfactory level as he informally tested it. The other group members recognised this success. Nonetheless, unequal engagement within each group and the dominance of some members were still evident.

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