Heliyon 10 (2024) e24278

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effects of reverse engineering pedagogy on students' learning performance in STEM education: The bridge-design project as an example

Baichang Zhong [a,*], Xiaofan Liu [a], Xinwei Li [b,**]

[a] School of Information Technology in Education, South China Normal University, No.55, West of Zhongshan Avenue, Guangzhou 510631, China
[b] Ministry of Secondary Vocational Education, Guangdong Open University (Guangdong Polytechnic Institute), No.162, Yunquan Road, Guangzhou, 510000, China

ARTICLE INFO

Keywords:
Bridge-design course
Engineering design
Project-based learning
Reverse engineering pedagogy
STEM education

ABSTRACT

In K-12 STEM education, engineering design is emphasized, as demonstrated by the bridge-design project. Due to the iterative nature of engineering design, engineering practice is frequently complicated and requires pedagogical guidance. As an emerging pedagogy in STEM education, REP (Reverse Engineering Pedagogy) is showing, but not enough, some benefits in several cases. This paper aims to explore the effects of REP in a bridge-design course. A comparison experiment, REP versus PBL (Project-Based Learning), was conducted by randomly forming two groups of fourth-grade students from a primary school in China. Results indicated that REP was more advantageous than PBL in terms of decreasing students' cognitive load, boosting their scientific knowledge level and engineering design skills. However, REP and PBL have the same effect on the students' learning attitude and engagement. The key findings, possible reasons, and suggestions for practice are also discussed.

1. Introduction

In an era of rising global challenges, STEM (Science, Technology, Engineering, and Mathematics) education has taken on the crucial mission of nurturing integrated talents [1–4]. A gamut of studies had evidenced that STEM education could strengthen students' skills required in the 21st century, involving problem-solving skills, collaborative abilities, critical thinking, creativity, etc [5–8]. Due to its enormous educational potentials, STEM education has been widely accepted as a global priority in schooling [9,10].

From a research and curricular standpoint, however, the dearth of a unified focus anchoring greater integration of the four STEM disciplines raises concerns [11–13]. Given the natural property to tie math and science together by addressing authentic problems, engineering has been recognized as the integrative glue in STEM implementation [14–16]. A prominent illustration of this is the integration of "science and engineering practices", "disciplinary core ideas", and "crosscutting concepts" within the Next Generation Science Standards (NGSS). These elements serve as performance expectations, defining what K-12 students should demonstrate to meet the standards [17].

Generally, engineering practice enables students to effectively address open-ended problems [18]. Based on this, a civil engineering

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: zhongbc@163.com (B. Zhong), 2446806277@qq.com (X. Li).

https://doi.org/10.1016/j.heliyon.2024.e24278
Received 19 April 2023; Received in revised form 30 December 2023; Accepted 5 January 2024

curriculum that focused primarily on the design and construction of buildings, bridges, and roads was established [19]. Among them, bridge design is favored by K-12 STEM education owing to its relative simplicity. In the bridge design process, students need to identify, comprehend, and apply the fundamental STEM concepts and principles to translate their designs into products [20]. Still, engineering practice is frequently complicated [21–23]. Due to the iterative nature of engineering design, students should be encouraged to repeatedly explore all aspects of the design process to optimize the solution or product until the design criteria are met [24]. Especially for students without prior knowledge, it is more difficult to fully consider, analyze and predict the feasibility of solutions within the limited class time [25,26].

Effective pedagogies are needed to guide students' engineering design performance. It is noteworthy that project-based learning (PBL) has been progressively introduced in STEM education in recent years. Whereas, PBL requires students to start from scratch until the entire project is completed, which necessitates both a strong student foundation and long teaching period [27]. In this context, reverse engineering pedagogy (REP) has initially shown its potential in STEM education, which allows students to start with a completed product/work, and then rebuild or optimize it, ultimately reaching the level of micro-innovation [28]. As a core component, product dissection could promote students' concept comprehension and contribute greatly to enhancing their design competency [29,30].

However, existing research has largely concentrated on the engineering courses in higher education, with little emphasis dedicated to the effects of REP in K-12 STEM education. For instance, the University of Missouri-Rolla endeavored to incorporate REP into traditional computer science courses. The results showed that 77 % of the students reported that REP reinforced the concepts covered in lectures, while 82 % expressed expectations in its integration into other courses, particularly those involving design [31]. Besides, Younis and Tutunji [32] described the experience of Philadelphia University in integrating REP into the engineering curriculum, including course objectives, methodology, content and evaluation. Moreover, third-year students from both Pennsylvania State University and Missouri University of Science and Technology undertook a coffee pot redesign project, which proved that product dissection could enhance product functionality and stimulate students' creativity [30]. Given the crucial role of initial education in fostering students' knowledge and skills for future learning and employment [33], it is vital to adopt REP in K-12 STEM education and verify its effects. Furthermore, there has been limited comparison between REP and PBL. Therefore, this paper aims to explore the effects of REP versus PBL in elementary STEM education by taking bridge-design project as an example.

2. Literature review

2.1. Bridge design in education

Bridge design has long been a favored instructional project that applies to various construction materials and techniques [34,35]. According to English and King [36], the design of bridge prototypes involves the application of STEM concepts. In science, for instance, students may grasp forces such as tension and compression, as well as how various bridge designs sustain a load, etc. For engineering and technology, students could recognize basic bridge types (e.g., beam, arch) and structures (e.g., trusses, beams, cross-bracing), etc. Meanwhile, students can apply distinct mathematical skills (e.g., spatial reasoning, estimation and measurement skills) to process various 2-D and 3-D shapes. Besides, Guzey, Moore, and Roehrig [19] and Hemming [37] stated that bridge activities may enhance students' problem-solving and cooperative skills, as well as reducing their anxiety in STEM disciplines. Consequently, bridge design is generally considered as an effective means of implementing STEM education [19,38].

Currently, there are two primary pathways for conducting bridge-design activities: competition and project-based learning (PBL). The former is designed to construct bridges in a gamified manner. For instance, through a competition-based experiment labeled "Design and Manufacture of Wooden Bridge". Barris, Torres, and Simon [39] observed that bridge-design competitions not only enhance students' mastery of certain disciplines such as the frame structure and material qualities of the bridge, but also boost their interdisciplinary knowledge. Differently, Hemming [37] further argued that bridge-design competitions are overly focused on forming physical performance rather than developing students' scientific thinking. Gradually, PBL was employed in paper bridge projects to develop students' 21st century skills (e.g., critical thinking, creative thinking, collaboration, communication, social skills, and leadership, etc.) [38]. In this regard, Zhao [40] concurred that instructors may regulate the instructional process in terms of time, cost, and quality while applying PBL in bridge-design activities. Conversely, Colliver [41] concluded that PBL was ineffective in boosting short-term learning, despite Norman and Schmidt [42] demonstrating that it could enhanced long-term learning. Similarly, Dochy, Segers, Bossche van den, and Gijbels [43] revealed that PBL had favorable effects on enhancing skills rather than knowledge. Moreover, Lin [44] stated that when incorporating PBL into a bridge-design course, student engagement was typically inadequate owing to the unclear division of labor. Based on this, a growing body of research has embraced competition as a PBL strategy for bridge-design project to facilitate students' engagement [38]. Nevertheless, the limited competition cycle is not effective in developing students' knowledge and skills in the PBL process.

To sum up, bridge-design projects are extensively employed in primary and secondary education nowadays, which have distinct advantage in cultivating students' practical skills. However, the current pedagogy has significant flaws as well.

2.2. Reverse engineering in education

The term "Reverse Engineering (RE)" derives from hardware analysis which refers to decipher a design from a finished product [45], which is based on the premise that a complex hardware system can be characterized as a hierarchical structure [46]. RE was first born in World War II and contributed immensely in the construction of military equipment such as airplanes and tanks. Nowadays, RE is progressively acknowledged as a viable means to shorten the product R&D cycle as a result of fierce market competition [47]. There is no general definition for RE to date, as each scholar defines it depending on their own research field. For instance, Chikofsky and Cross [45] defined RE as "the process of analyzing a subject system to identify the system's components and their interconnections, and to create representations of a system in another form at a higher level of abstraction". Abella, Daschbach, and McNichols [48] described RE as "the basic concept of producing a part based on an original or physical model without utilizing engineering drawing". Huang [49] considered RE is a redesign process that maximizes the usage of current design principles and key technologies.

In the late 20th century, RE was formally introduced into education, which sparked the focus of a variety of scholars. For instance, a 10-step REP proposed by Otto and Wood [50] has been widely utilized in higher education. According to related research, the 10-step REP could effectively meet the demands of students with diverse learning styles, but the operation time and iteration design should be improved [23,51]. Besides, another representative REP is the "disassembly-analysis-assembly" (DAA) model developed by Ogot and Kremer [52], which has been extensively researched in dissection activities [30,53]. Generally, DAA activities may be categorized based on two dimensions: teachers' guidance degree and students' engineering expertise. Through the intersection of the two dimensions, four learning activities could be distinguished: exposing, inspiring, investigating, and discovering. Furthermore, anchoring two different STEM orientations (i.e., product development and scientific inquiry), Zhong et al. [54] divided REP into two categories (i.e., recovery and reconstruction), as showed in Fig. 1. The REP adopted in this study was also proposed, which is a five-step deconstructive recovery experiment: experience and analysis; decomposition and restoration; redesign and micro-innovation; prototyping or re-engineering; evaluation and reflection.

The application of REP has substantially risen in recent years. Substantial studies have confirmed that REP could (1) expedite the product development process [21,49], (2) promote students' learning motivation [55], (3) enhance students' creativity, hands-on ability and communication skills [28,30], and reduce the difficulty of engineering design [50]. For instance, according to Grantham et al. [30], students who engaged in dissection prior to the redesign exhibited higher creativity and better product functionality than those who did not. Similarly, Akerdad, Aboutajeddine and Elmajdoubi [56] demonstrates that the integration of REP and engineering education can provide students with a more effective engineering design process. Besides, Otto and Wood [50] found that REP could decrease the difficulty of subsequent engineering design (i.e., a key element affecting cognitive load) by exposing students to the full operational process early. Another study from Okudan and Mohammed [57] observed that students held favorable attitudes towards dissection, particularly with regards to its impact on redesign. Moreover, Elizalde et al. [58] claimed that collaborative REP has a positive effect on students' ability to synthesize knowledge via experiment assembly. Meanwhile, a separate study conducted by the Zhong and Li [59] revealed that collaborative learning was not always superior to individual learning in REP in terms of troubleshooting, which implies other factors should be further investigated. Another study conducted by the Zhong, Kang and Zhan [28] obtained no significant difference in learning attitude towards the course between REP and FFP (i.e., Forward Project Pedagogy).

Generally, existing research evidenced that REP holds certain educational potential. Compared to traditional PBL, it not only minimizes learning time, but also requires less skills from students. However, REP in K-12 STEM education is less practiced. Especially, whether incorporating REP into bridge-design projects can improve students' learning performance remains to be explored.

3. Research questions

Effective pedagogy should dedicate to reduce students' external cognitive load while enhancing their interests, expertise, and skills [60]. Considering the positive correlation between learning interest, attitude and immersion [28], this study will explore the effect of REP on pupils in a bridge-design course in the following aspects: cognitive load, learning attitude, learning engagement, scientific knowledge level and engineering design skills. Accordingly, five research questions will be answered in this paper.

1. Can REP decrease students' cognitive load?
2. Can REP improve students' learning attitude?
3. Can REP improve students' learning engagement?
4. Can REP enhance students' scientific knowledge level?
5. Can REP develop students' engineering design skills?

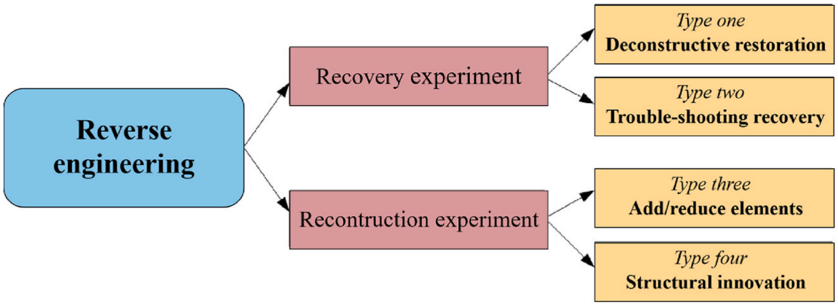


Fig. 1. Classification framework of REP.

The research hypotheses are stated as follows.

1. REP could decrease students' cognitive load.
2. REP could improve students' learning attitude.
3. REP could improve students' learning engagement.
4. REP could enhance students' scientific knowledge level.
5. REP could develop students' engineering design skills.

4. Research design

4.1. Participants

Given the spatial limitations of the experiment and the potential difficulties associated with bridge construction for younger students (grades 1–3), this study selected a sample of 32 fourth-grade pupils from a prestigious public elementary school in Guangzhou, China. All students were enrolled voluntarily and free. Neither the engineering nor STEM courses had been taken by these students previously. Learning attitude survey and prior knowledge quiz were implemented before the experiment, and the results revealed that there was no significant difference between the two classes.

During the experiment, 32 students were randomly divided into two classes. Sample information is shown in Table 1. Different learning models were applied in the two classes to develop a bridge-design course: the control class studied via PBL, while the experimental class studied via REP. Both classes collaborated in pairs to design and construct a paper bridge with optimal load bearing capacity.

4.2. Procedure

The experiment lasted for 2 days in all. The experiment duration of each class was one day with 8 h. Except for the difference in pedagogy, the experimental class and the control class have identical instructional material, instructors, and teaching assistants.

In the 1st hour, all students participated in a prior knowledge quiz and a learning attitude survey. Besides, students paired up freely and acquired knowledge and principles related to bridge.

From the 2nd to the 6th hour, students were required to design, build, and optimize their own paper bridges. The experimental classes employed REP that adhered to the following instructional steps, including (1) experience and analysis: students experience the bridge and analyze its characteristics; (2) decomposition and restoration: students decompose the bridge and observe its structure; (3) redesign and micro-innovation: students achieve "micro-innovation" by adding or subtracting certain elements of the bridge; (4) prototyping or re-engineering: students analyze the flaws of existing bridges and reconstruct the bridges based on actual needs; and (5) evaluation and reflection: students summarize and evaluate the reconstructed bridge and procedure.

The control class adopted PBL, which followed the instructional steps specified by Zhong et al. [54], including (1) requirements analysis and problem definition: students define the goals of bridge construction based on actual needs; (2) design alternative solutions: students design multiple bridge construction solutions based on their goals; (3) design solution in detail: students select and refine the optimal solution through comprehensive evaluation; (4) implementation and testing: students construct a bridge based on their design solution and (5) presentation and evaluation: students share and present their bridges for evaluation.

In the 7th hour, students were required to report and share their paper bridges from the dimensions of scientificity, originality, aesthetic degree, economic efficiency, and stability.

In the 8th hour, scientific knowledge quiz, learning attitude survey, learning engagement survey, cognitive load measurement, and load bearing test of paper bridge were conducted. The detailed schedule is shown in Table 2.

4.3. Materials

Two sorts of teaching materials were covered in this study.

Experiment tools. Several tools were employed in the experiment, including: papers, glue, wooden sticks, cotton thread, scissors, electronic weight scales, weights, etc. Electronic weight scales and weights were primarily used for load bearing test, while other tools were utilized in the construction of paper bridges.

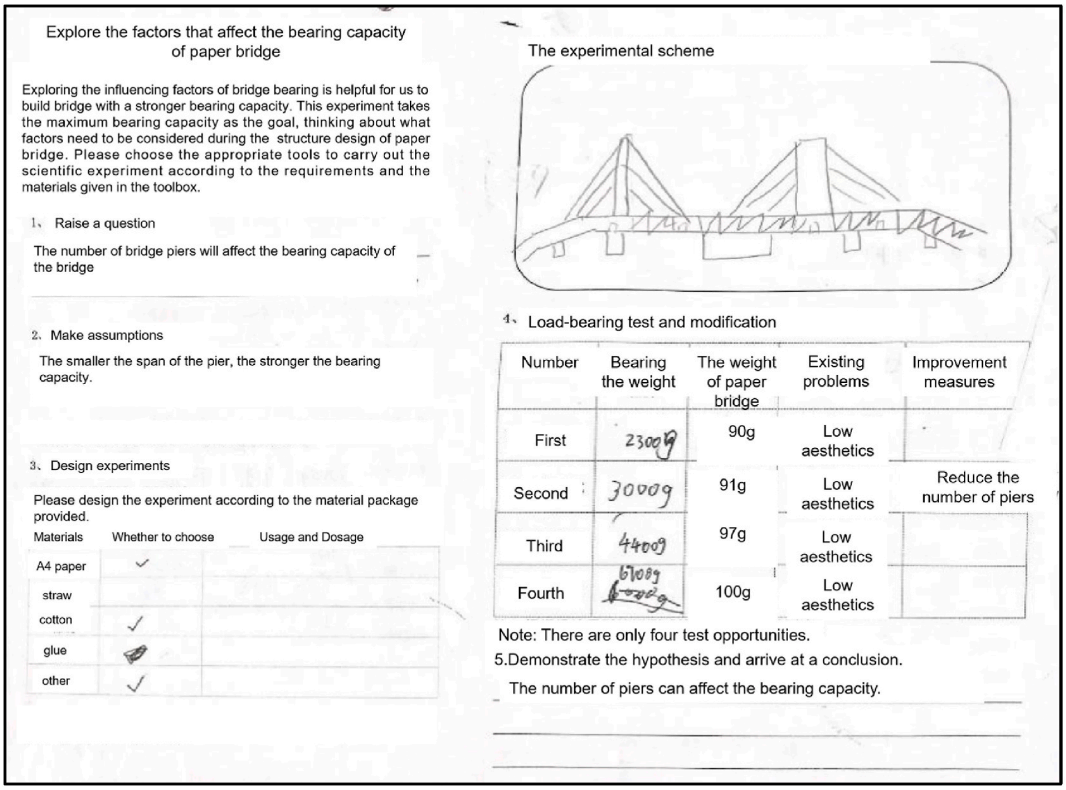
Handbook for bridge design. To monitor students' scientific inquiry process, PBL handbook (see Fig. 2) and REP handbook (see Fig. 3) were developed to assist students with designing, constructing and optimizing their paper bridges. These handbooks were distributed prior to each class session and collected after each class session. The instructor would remind those pupils whose

Table 1
Sample characteristics.

Class	Learning model	Class size	Boys	Girls	Age
Control class	PBL	16	11	5	9–10
Experimental class	REP	16	10	6	9–10
Total	–	32	21	11	–

Table 2
Schedule of the experiment.

Class hour	Contents
1st	Prior knowledge quiz, learning attitude survey Learn the related basic knowledge and consider the factors affecting the load bearing of bridges
2nd	Learn scientific inquiry process and conduct scientific inquiry experiments
3–4th	Design the paper bridge scheme and sketch the paper bridge
5–6th	Construct, optimize and improve the paper bridge, carry on the load bearing test
7th	Share, reflect and evaluate the paper bridge
8th	Posterior knowledge quiz, learning attitude survey, learning engagement survey, cognitive load measurement, load bearing test of paper bridge



Explore the factors that affect the bearing capacity of paper bridge

Exploring the influencing factors of bridge bearing is helpful for us to build bridge with a stronger bearing capacity. This experiment takes the maximum bearing capacity as the goal, thinking about what factors need to be considered during the structure design of paper bridge. Please choose the appropriate tools to carry out the scientific experiment according to the requirements and the materials given in the toolbox.

1、 Raise a question

The number of bridge piers will affect the bearing capacity of the bridge

2、 Make assumptions

The smaller the span of the pier, the stronger the bearing capacity.

3、 Design experiments

Please design the experiment according to the material package provided.

Materials	Whether to choose	Usage and Dosage
A4 paper	✓	
straw		
cotton	✓	
glue	✓	
other	✓	

The experimental scheme

4、 Load-bearing test and modification

Number	Bearing the weight	The weight of paper bridge	Existing problems	Improvement measures
First	2300g	90g	Low aesthetics	
Second	3000g	91g	Low aesthetics	Reduce the number of piers
Third	4400g	97g	Low aesthetics	
Fourth	6708g ~~[illegible]~~	100g	Low aesthetics	

Note: There are only four test opportunities.

5.Demonstrate the hypothesis and arrive at a conclusion.

The number of piers can affect the bearing capacity.

Fig. 2. Handbook for PBL.

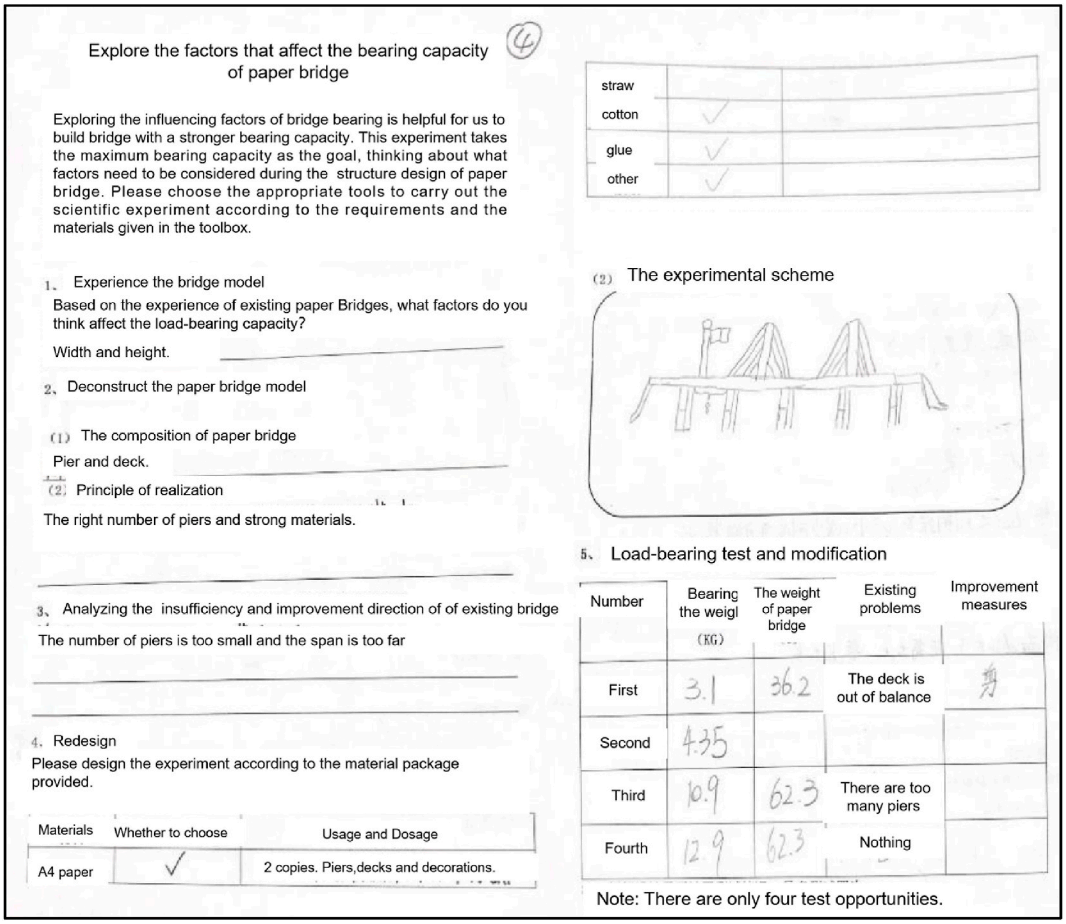
handbooks were incomplete.

4.4. Measures

An experimental design was employed to examine the effects of REP and PBL on students' learning performance (see Fig. 4). In this study, students' learning performance was assessed from learning process (i.e., cognitive load, learning attitude, and learning engagement) and learning outcome (i.e., scientific knowledge level and engineering design skills). The instruments for the pretest and posttest are shown in Table 3. The load bearing test of paper bridge, evaluation criteria for paper bridge and experimental worksheet were utilized to represent students' engineering design skills. All students completed the pretest and posttest individually.

Cognitive load measurement. Research has indicated that task types could affect cognitive development. For instance, complex tasks comprise a large quantity of interacting information pieces, resulting in a high working memory load, also known as intrinsic cognitive load [60]. The bridge-design project includes several challenging procedures such as engineering design and construction. Thus, it is vital to assess the cognitive load required by pupils to complete a paper bridge project. A 9-point, two-question scale ranging from 1 ("extremely low effort/difficulty") to 9 ("extremely high effort/difficulty") was used to estimate students' mental effort and perceived difficulty in completing the project [61]. This subjective measure of cognitive load has been proved to be valid and reliable by various studies [64,65].

Learning attitude survey. Attitude is one of the most crucial indicators of students' learning status. A modified five-point Likert-scale from Bishop-Clark, Courte, and Howard [62] was applied to assess students' confidence, enjoyment, and value towards the paper



Explore the factors that affect the bearing capacity of paper bridge ④

Exploring the influencing factors of bridge bearing is helpful for us to build bridge with a stronger bearing capacity. This experiment takes the maximum bearing capacity as the goal, thinking about what factors need to be considered during the structure design of paper bridge. Please choose the appropriate tools to carry out the scientific experiment according to the requirements and the materials given in the toolbox.

1、 Experience the bridge model

Based on the experience of existing paper Bridges, what factors do you think affect the load-bearing capacity?

Width and height.

2、 Deconstruct the paper bridge model

(1) The composition of paper bridge

Pier and deck.

(2) Principle of realization

The right number of piers and strong materials.

3、 Analyzing the insufficiency and improvement direction of of existing bridge

The number of piers is too small and the span is too far

4、 Redesign

Please design the experiment according to the material package provided.

Materials	Whether to choose	Usage and Dosage
A4 paper	✓	2 copies. Piers,decks and decorations.
straw		
cotton	✓	
glue	✓	
other	✓	

(2) The experimental scheme

5、 Load-bearing test and modification

Number	Bearing the weigl (KG)	The weight of paper bridge	Existing problems	Improvement measures
First	3.1	36.2	The deck is out of balance	剪
Second	4.35			
Third	10.9	62.3	There are too many piers	
Fourth	12.9	62.3	Nothing	

Note: There are only four test opportunities.

Fig. 3. Handbook for REP.

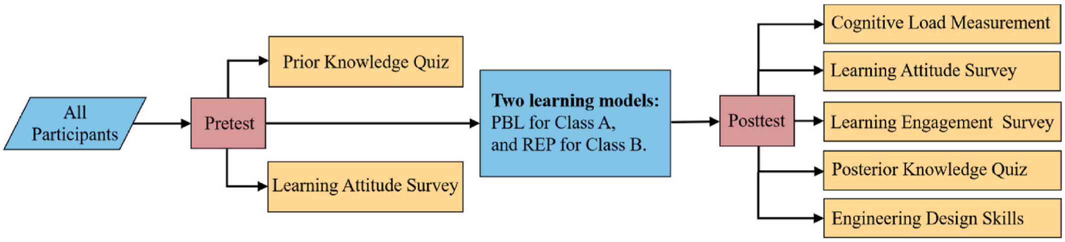


Fig. 4. Overview of the experimental design.

bridge course. The survey is delineated in Electronic Supplemental Materials. All students completed the same survey before and after the experiment. Their reliability coefficients of this study were all higher than 0.75.

Learning engagement survey. Learning engagement refers to the extent to which students are involved in the learning process [66]. Similar to the learning attitude survey, a five-point Likert-scale derived from Fredricks et al. [63] was employed. Engagement is primarily manifested in three dimensions: behavioral, emotional and cognitive immersion. The questions used for each dimension are delineated in Electronic Supplemental Materials.

Prior/Posterior knowledge quiz. The Prior/Posterior knowledge quiz aimed to examine students' scientific knowledge level. It consists of 15 questions from six dimensions: bridge fundamentals, state change, gravity, bending capacity, tool usage, and structural stability. For instance, what three parts make up a bridge? Which of the following structures is not stable? The authors conducted a pretest and posttest on students' scientific knowledge level respectively.

Load bearing test of paper bridge. Each group was given four opportunities to test the load bearing of their paper bridges. After each load bearing test, students were required to record the results on the load bearing test table and modify their paper bridges (see

Table 3
Instruments for data collections.

Instrument	Construct	Source	Cronbach's alpha
Cognitive load measurement (Posttest)	Mental effort (1 question) Task difficulty (1 question)	Paas [61]	–
Learning attitude survey (Pretest & Posttest)	Confidence (5 questions) Enjoyment (5 questions) Value (5 questions)	Bishop-Clark et al. [62] Zhong and Li [59]	.84
Learning engagement survey (Posttest)	Behavioral (5 questions) Emotional (5 questions) Cognitive (4 questions)	Fredricks et al. [63]	.88
Prior/Posterior knowledge quiz (Pretest & Posttest)	See text description	Self-developed	–
Load bearing test of paper bridge (Posttest)	See the 4th part in Figs. 2 and 3	Self-developed	–
Evaluation criteria for experimental worksheet (Posttest)	See text description	Self-developed	–
Evaluation criteria for paper bridge (Posttest)	See text description	Self-developed	–

the 4th part in Figs. 2 and 3). The actual scenario of the load bearing test is shown in Fig. 5.

Evaluation criteria for paper bridge. To completely evaluate students' learning outcomes, the authors designed the evaluation criteria for paper bridge in five dimensions: scientificity, originality, aesthetic degree, economic efficiency, and stability.

Evaluation criteria for experimental worksheet. To evaluate students' engineering design skills from a process perspective, the authors quantified the content of the completed worksheets (see Figs. 2 and 3) through pre-designed evaluation criteria, involving four dimensions: integrity, standardness, novelty, and consistency.

4.5. *Research ethics*

The work described here was approved by the ethical committees of South China Normal University. In accordance with SCNU regulations, all students were given informed consent as part of their registration into the course, which was cosigned by their parents.

5. Results

In order to address the research questions presented in Section 3, Mann-Whitney U tests were administrated to identify differences. For the dimensions showing a significant difference ($p < 0.05$), Cohens' d will be used to evaluate the magnitude of the difference. A 'd' value falling within the range of 0.2–0.5 signifies a small effect size, while a 'd' value between 0.5 and 0.8 denotes a medium effect size. A 'd' value exceeding 0.8 indicates a large effect size.

5.1. *Cognitive load*

Table 4 demonstrated that there was a significant difference in cognitive load between REP and PBL ($p < 0.01$, $d = 1.315 > 0.8$). Besides, REP group ($M = 11.34$) perceived less cognitive load than PBL group ($M = 21.66$). Therefore, Hypothesis 1 was valid.

5.2. *Learning attitude towards the course*

As shown in Table 5, there was no significant difference in students' learning attitudes between REP and PBL ($p > 0.05$). Therefore,

Fig. 5. Load bearing test of paper bridges.

Table 4

Difference in cognitive load between PBL and REP.

Experimental variable	Group	N	Mean	Mann-Whitney U	Z	P	Cohen'd
Cognitive load	REP	16	11.34	45.500	−3.130	.002**	1.315
	PBL	16	21.66				

Note: **$p < 0.01$.

Hypothesis 2 was invalid.

5.3. *Learning engagement in the course*

A comparison of students' learning engagement (see Table 6) indicated that there was no significant difference between REP and PBL ($p > 0.05$). Therefore, Hypothesis 3 was invalid.

5.4. *Scientific knowledge level*

Table 7 showed that there was a significant difference between REP and PBL ($p < 0.05$, $d = 1.068 > 0.8$) in scientific knowledge level. Besides, in terms of the mean, REP group ($M = 20.72$) had significantly higher scientific knowledge level than PBL group ($M = 12.28$). Therefore, Hypothesis 4 was valid.

5.5. *Engineering design skills*

Students' engineering design skills were compared in three dimensions: load bearing of paper bridge, evaluation of paper bridge and experimental worksheet. To ensure the validity of the evaluation of paper bridge and experimental worksheet, the instructor and five teaching assistants were selected as evaluators based on the same criteria. The final scores were determined by averaging the ratings provided by the three raters with the highest Kendall's harmony coefficient. The results showed that both the paper bridge scores ($W = 0.602$, $p < 0.05$) and the worksheet scores ($W = 0.887$, $p < 0.01$) had strong consistency.

Load bearing of paper bridges. Table 8 showed that there was no significant difference between REP and PBL in load bearing of paper bridges ($p > 0.05$). To visually compare the load bearing of the paper bridges in both classes, a box diagram (see Fig. 6) was presented to illustrate the superior load bearing of the paper bridges in the REP group.

Difference in paper bridges. As shown in Table 8, the paper bridge between REP and PBL did not differ significantly ($p > 0.05$), however, the originality subdimension differed significantly ($p < 0.05$, $d = 1.175 > 0.8$). Besides, in terms of the mean, the originality of paper bridges in REP group ($M = 6.06$) was lower than that in PBL group ($M = 10.94$).

Difference in experimental worksheets. Table 8 indicated that there was a significant difference between REP and PBL in experimental worksheets ($p < 0.01$, $d = 2.530 > 0.8$). Besides, all sub-dimensions of experimental worksheets in REP were higher than those in PBL based on the mean value.

Overall, there were significant differences between REP and PBL in terms of engineering design skills ($p < 0.01$, $d = 1.591 > 0.8$). In terms of mean, REP ($M = 11.69$) was superior to PBL ($M = 5.31$). Therefore, Hypothesis 5 was valid.

6. Discussions

6.1. *REP outperforms PBL in decreasing students' cognitive load*

Consistent with prior studies, our study found that REP was beneficial in decreasing students' cognitive load. Accordingly, the benefits of REP in bridge-design course are further validated. This result may be explained in two sides of the coin.

From one side of the coin, this might lie on scaffolding, which is vital in the problem-solving process to decrease students' cognitive load [64,67]. Scaffolding in our study pointed to the existing paper bridges. Specifically, students in REP could gain early exposure in fully operational and functional processes by experiencing, analyzing, disassembling, assembling, and redesigning existing paper

Table 5

Difference in learning attitude between PBL and REP.

Experimental variable	Group	N	Mean	Mann-Whitney U	Z	P
Confidence	REP	16	17.06	119.000	−.341	.733
	PBL	16	15.94			
Enjoyment	REP	16	17.56	111.000	−.644	.519
	PBL	16	15.44			
Value	REP	16	18.69	93.000	−1.328	.184
	PBL	16	14.31			
Total	REP	16	17.91	105.500	−.850	.395
	PBL	16	15.09			

Table 6
Difference in learning engagement between PBL and REP.

Experimental variable	Group	N	Mean	Mann-Whitney U	Z	P
Behavioral immersion	REP	16	18.00	104.000	−.912	.362
	PBL	16	15.00			
Emotional immersion	REP	16	18.44	97.000	−1.178	.239
	PBL	16	14.56			
Cognitive immersion	REP	16	18.41	97.500	−1.161	.245
	PBL	16	14.59			
Total	REP	16	18.41	97.500	−1.153	.249
	PBL	16	14.59			

Table 7
Difference in scientific knowledge level between PBL and REP.

Experimental variable	Group	N	Mean	Mann-Whitney U	Z	P	Cohen'd
Scientific knowledge level	REP.	16	20.72	60.500	−2.555	.011*	1.068
	PBL	16	12.28				

Note: *$p < 0.05$.

Table 8
Difference in engineering design skills between PBL and REP.

Experimental variable	Sub-dimensions	Group	N	Mean	Mann-Whitney U	Z	P	Cohen'd
Load bearing	–	REP	8	9.88	21.000	−1.158	.279	–
		PBL	8	7.13				
Paper bridge	Scientificity	REP	8	9.75	22.000	−1.061	.289	–
		PBL	8	7.25				
	Originality	REP	8	6.06	12.500	−2.063	.039*	1.175
		PBL	8	10.94				
	Aesthetics degree	REP	8	8.31	30.500	−.162	.871	–
		PBL	8	8.69				
	Economic efficiency	REP	8	7.25	22.000	−1.057	.290	–
		PBL	8	9.75				
	Stability	REP	8	9.31	25.500	−.688	.491	–
		PBL	8	7.69				
	Total	REP	8	8.44	31.500	−.053	.958	–
		PBL	8	8.56				
Experimental worksheet	Integrity	REP	8	12.25	2.000	−3.162	.002**	2.713
		PBL	8	4.75				
	Standardness	REP	8	12.00	4.000	−2.956	.003**	2.146
		PBL	8	5.00				
	Innovation	REP	8	11.44	8.500	−2.479	.013*	1.488
		PBL	8	5.56				
	Consistency	REP	8	12.13	3.000	−3.068	.002**	2.045
		PBL	8	4.88				
	Total	REP	8	12.38	1.000	−3.258	.001**	2.530
		PBL	8	4.63				
Total	–	REP	8	11.69	6500	−2.688	.005**	1.591
		PBL	8	5.31				

Note: *$p < 0.05$, **$p < 0.01$.

bridges [68].

From another side, this may be related to the collaborative learning advocated in REP [53]. Just as Okudan and Mohammed [57] concurred, design teams that contained dissection activities reported greater workload sharing and team satisfaction. Consequently, the cognitive load of students in REP group was lower than that in PBL group.

6.2. No significant difference in students' learning attitude and engagement between PBL and REP

Previous research has reported that REP-instructed students exhibit better attitude [57]. Whereas, in our study, there was no statistically significant difference in students' learning attitude and engagement between PBL and REP. This result may be explained in two angles.

Firstly, since most students have no prior exposure to bridge-design projects, designing and constructing bridges is a high novelty for them. Additionally, previous studies have indicated there is a positive correlation between interest and novelty [66,69]. Thus the

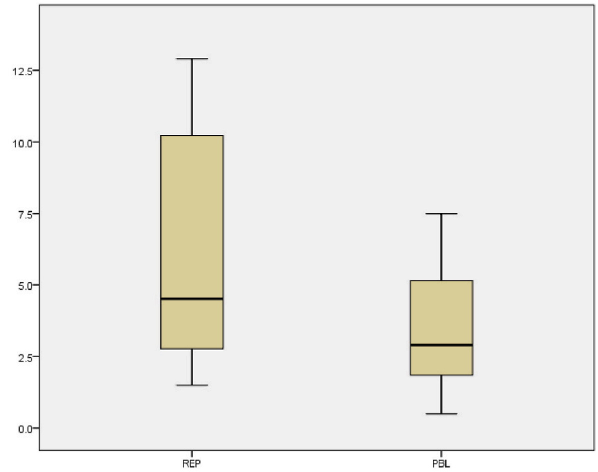


Fig. 6. Comparison of paper bridges' bearing results between REP and PBL.

result is not surprised since there is also a positive correlation between interest and attitude [28,69].

Secondly, the majority of students could complete the work with moderate effort, which contributed to their positive attitude and confidence in the bridge-design project [70]. Especially, students are progressively immersed in the entire process from design to construction. Thus, students in both REP and PBL groups would maintain their interest and engagement in the learning process.

6.3. REP outperforms PBL in improving students' scientific knowledge level

With the inclusion of engineering in the Next Generation Science Standards, the conceptual and methodological links between science and engineering are emphasized [71,72]. Our study noted that students' scientific knowledge level in REP group were considerably higher than those in PBL group. Perhaps this is because REP helps students continuously learn and apply related concepts during the disassembly and assembly process [49,55,58]. Besides, REP also strengthen students' conceptual understanding by observation, experiencing, reflection, and questioning [28].

6.4. REP outperforms PBL in improving students' engineering design skills

Echoing previous studies [30], our studies observed that students' engineering design skills in REP group were clearly superior to those in PBL group. Meanwhile, existing research also claimed that product disassembly delivered a wealth of ideas for product redesign [73]. In REP groups, students may analyze design requirements more precisely and focused on micro-innovations consciously [28]. However, our study found that paper bridges in REP did not differ substantially from those in PBL in scientificity, aesthetics degree, economic efficiency and stability, and even fared poorly in terms of originality. Through classroom observation, REP students are more concerned with the load bearing of paper bridges. Anchoring it, the students preferred analyzing the flaws of the existing works to construct new paper bridges with higher load bearing. Particularly when students have witnessed the interior elements during product disassembly, they may be limited to a single solution [30]. Accordingly, the students in REP group simply added or subtracted elements from the existing paper bridges rather than remodeling them structurally. In this vein, students should be encouraged to propose varied product-based solutions in their REP practice.

7. Conclusion and Implications

Given that previous research mainly emphasized the application of REP in higher education, this study introduces REP into K-12 STEM education to proactively equip students with essential skills for future study and employment. Taking bridge-design project as an example, a quasi-experiment was adopted in this study to examine the effects of REP. The students' performance was evaluated from five aspects: cognitive load, learning attitude, learning engagement, scientific knowledge level, and engineering design skills.

We randomly selected two classes to conduct a two-day experiment. The experimental class adopted the REP, whereas the control class adopted the PBL. Relevant information was collected through questionnaires and tasks. The results illustrated that REP is more beneficial to decreasing students' cognitive load, enhancing their scientific knowledge level and engineering design skills than PBL. However, REP and PBL have the same effect on students' learning attitude and engagement.

Notably, introducing REP into education entails more than simply shifting the RE process from the industrial to the educational realm. Evidently, as an integral part of product-oriented learning, more emphasis should be placed on students' creativity [30,74]. Therefore, teachers should not only encourage students to generate varied solutions, but also provide timely scaffolding for them. For instance, certain rapid prototyping tools (e.g., 3D printing, laser cutting, etc.) may be employed in project development to expedite structural transformation [28]. In addition, when utilizing REP, teachers should guide students to consider the initial design intent with empathy, which facilitates the identifying of its flaws and the completion of product redesign.

Limitations and future research

There are some limitations to this research.

First, the sample size was small and confined to primary school students, thus the conclusions may not be valid for middle school students. To validate the probable difference, future research could be conducted with middle school and high school students. Meanwhile, the effects of REP on engineering projects of varying difficulty in STEM fields can be explored.

Second, the experimental duration of this study was short. Future research should suitably prolong the experimental duration and follow up students' learning and even their career development for an extended period.

Third, considering the several results of this study were not significant, future research could employ more qualitative methodologies such as classroom observations and interviews to enhance the validity of the findings. More importantly, this type of qualitative data enables us to explore the potential effects of REP on students' cooperation and communication skills.

Ethics declarations

All participants provided informed consent to participate in the study.

Funding

This study is funded by the General Project for Education from National Social Science Fund of China (Study on 4C Teaching Model for Cultivating Students' Interdisciplinary Creativity, Grant Number: BCA220219).

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Baichang Zhong: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Xiaofan Liu:** Writing – original draft, Formal analysis, Data curation. **Xinwei Li:** Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e24278.

References

[1] E.L. Adams, The effect of a middle grades STEM initiative on students' cognitive and non-cognitive outcomes, Stud. Educ. Eval. 68 (2021) 100983, https://doi.org/10.1016/j.stueduc.2021.100983.

[2] L.D. English, Advancing elementary and middle school STEM education, Int. J. Sci. Math. Educ. 15 (1) (2017) 5–24, https://doi.org/10.1007/s10763-017-9802-x.

[3] T.R. Kelley, J.G. Knowles, A conceptual framework for integrated STEM education, International Journal of STEM Education 3 (11) (2016) 1–11, https://doi.org/10.1186/s40594-016-0046-z.

[4] C.S. Lai, Using inquiry-based strategies for enhancing students' STEM education learning, Journal of Education in Science Environment and Health 4 (1) (2018) 110–117, https://doi.org/10.21891/jeseh.389740.

[5] E.B. Altan, S. Tan, Concepts of creativity in design based learning in STEM education, Int. J. Technol. Des. Educ. 31 (3) (2020) 503–529, https://doi.org/10.1007/s10798-020-09569-y.

[6] R. Lavi, M. Tal, Y.J. Dori, Perceptions of STEM alumni and students on developing 21st century skills through methods of teaching and learning, Stud. Educ. Eval. 70 (2021) 101002, https://doi.org/10.1016/j.stueduc.2021.101002.

[7] S. Fan, K. Yu, Core value and implementation of the science, technology, engineering, and mathematics curriculum in technology education, Journal of Research in Education Sciences 61 (2) (2016) 153–183, https://doi.org/10.6209/JORIES.2016.61(2).06.

[8] N.M. Siew, H. Goh, F. Sulaiman, Integrating STEM in an engineering design process: the learning experience of rural secondary school students in an outreach challenge program, J. Baltic Sci. Educ. 15 (4) (2016) 477–493.

[9] L. Johnson, S. Adams, V. Estrada, S. Martín, Technology Outlook for STEM+ Education 2013-2018: an NMC Horizon Project Sector Analysis, The New Media Consortium, Austin, Texas, 2013.

[10] Y. Li, K. Wang, Y. Xiao, J.E. Froyd, Research and trends in STEM education: a systematic review of journal publications, International Journal of STEM Education 7 (1) (2020) 1–16, https://doi.org/10.1186/s40594-020-00207-6.

[11] B.S. Barrett, A.L. Moran, J.E. Woods, Meteorology meets engineering: an interdisciplinary STEM module for middle and early secondary school students, International Journal of STEM Education 1 (1) (2014) 1–7, https://doi.org/10.1002/j.2168-9830.2000.tb00545.x.

[12] National Research Council, STEM Learning Is Everywhere: Summary of a Convocation on Building Learning Systems, The National Academies Press, Washington, DC, 2014.

[13] STEM Taskforce Report, Innovate: a Blueprint for Science, Technology, Engineering, and Mathematics in California Public Education, Californians Dedicated to Education Foundation, Dublin, California, 2014. http://www.cde.ca.gov/nr/ne/yr14/yr14rel71.asp.

[14] C.V. McDonald, STEM Education: a review of the contribution of the disciplines of science, technology, engineering and mathematics, Sci. Educ. Int. 27 (4) (2016) 530–569, https://doi.org/10.1186/s40594-020-00207-6.

[15] T.J. Moore, A.W. Glancy, K.M. Tank, J.A. Kersten, K.A. Smith, M.S. Stohlmann, A framework for quality K-12 engineering education: research and development, Journal of Pre-college Engineering Education Research (J-PEER) 4 (1) (2014) 2, https://doi.org/10.7771/2157-9288.1069.

[16] G. Strimel, M.E. Grubbs, Positioning technology and engineering education as a key force in STEM education, J. Technol. Educ. 27 (2) (2016) 21–36, https://doi.org/10.21061/jte.v27i2.a.2.

[17] Next Generation Science Standards (NGSS), MS-ETS1 Engineering Design, 2014. https://www.nextgenscience.org/dci-arrangement/ms-ets1-engineering-design.

[18] Y. Li, Z. Huang, M. Jiang, T.W. Chang, The effect on pupils' science performance and problem-solving ability through Lego: an engineering design-based modeling approach, Journal of Educational Technology & Society 19 (3) (2016) 143–156. https://www.jstor.org/stable/jeductechsoci.19.3.143.

[19] S.S. Guzey, T.J. Moore, G.H. Roehrig, in: Limon E. Kattington (Ed.), Curriculum Development for STEM Integration: Bridge Design on the White Earth Reservation, Handbook of Curriculum Development, 2010, pp. 347–366.

[20] T. Lewis, Coming to terms with engineering design as content, J. Technol. Educ. 16 (2) (2005) 37–54, https://doi.org/10.21061/jte.v16i2.a.3.

[21] R.S. Lee, J.P. Tsai, Y.C. Kao, G.C. Lin, K.C. Fan, STEP-based product modeling system for remote collaborative reverse engineering, Robot. Comput. Integrated Manuf. 19 (6) (2003) 543–553, https://doi.org/10.1016/S0736-5845(03)00064-4.

[22] I. Jawaid, M.Y. Javed, M.H. Jaffery, A. Akram, U. Safder, S. Hassan, Robotic system education for young children by collaborative-project-based learning, Comput. Appl. Eng. Educ. 28 (1) (2020) 178–192, https://doi.org/10.1002/cae.22184.

[23] K.L. Wood, D. Jensen, J. Bezdek, K.N. Otto, Reverse engineering and redesign: courses to incrementally and systematically teach design, J. Eng. Educ. 90 (3) (2001) 363–374, https://doi.org/10.1002/j.2168-9830.2001.tb00615.x.

[24] T.J. Moore, K.A. Smith, Advancing the state of the art of STEM integration, Journal of STEM Education 15 (1) (2014) 5–10.

[25] M. Nückles, J. Roelle, I. Glogger-Frey, J. Waldeyer, A. Renkl, The self-regulation-view in writing-to-learn: using journal writing to optimize cognitive load in self-regulated learning, Educ. Psychol. Rev. 32 (2020) 1089–1126, https://doi.org/10.1007/s10648-020-09541-1.

[26] J. Wirth, F. Stebner, M. Trypke, C. Schuster, D. Leutner, An interactive layers model of self-regulated learning and cognitive load, Educ. Psychol. Rev. 32 (4) (2020) 1127–1149, https://doi.org/10.1007/s10648-020-09568-4.

[27] J.R. Savery, Overview of problem-based learning: definitions and distinctions, Interdisciplinary Journal of Problem-based Learning 1 (1) (2015) 9–20, https://doi.org/10.7771/1541-5015.1002.

[28] B. Zhong, S. Kang, Z. Zhan, Investigating the effect of reverse engineering pedagogy in K-12 robotics education, Comput. Appl. Eng. Educ. 29 (5) (2021) 1097–1111.

[29] A. Bertoni, A reverse engineering role-play to teach systems engineering methods, Educ. Sci. 9 (1) (2019) 30, https://doi.org/10.3390/educsci9010030.

[30] K. Grantham, G.E. Okudan Kremer, T.W. Simpson, O. Ashour, A study on situated cognition: product dissection's effect on redesign activities, Advances in Engineering Education 3 (4) (2013) 617–626, https://doi.org/10.1115/DETC2010-28334.

[31] M.R. Ali, Why teach reverse engineering? Software Eng. Notes 30 (4) (2005) 1–4.

[32] M.B. Younis, T. Tutunji, Reverse engineering course at Philadelphia University in Jordan, Eur. J. Eng. Educ. 37 (1) (2012) 83–95, https://doi.org/10.1080/03043797.2012.658508.

[33] B. Bevan, J.P. Gutwill, M. Petrich, K. Wilkinson, Learning through STEM-rich tinkering: findings from a jointly negotiated research project taken up in practice, Sci. Educ. 99 (1) (2015) 98–120.

[34] D.R. Carroll, Bridge engineering for the elementary grades, J. Eng. Educ. 86 (1997) 221–226, https://doi.org/10.1002/j.2168-9830.1997.tb00288.x.

[35] L.D. English, P.B. Hudson, L. Dawes, Engineering design processes in seventh-grade classrooms: bridging the engineering education gap, Eur. J. Eng. Educ. 37 (5) (2012) 436–447, https://doi.org/10.1080/03043797.2012.708721.

[36] L.D. English, D. King, STEM integration in sixth grade: desligning and constructing paper bridges, Int. J. Sci. Math. Educ. 17 (5) (2019) 863–884, https://doi.org/10.1007/s10763-018-9912-0.

[37] J. Hemming, Drawbridge by design: civil engineering for middle school, Technology and Engineering Teacher 77 (7) (2018) 40–44.

[38] L.R. Barroso, S.B. Nite, J.R. Morgan, A. Bicer, R.M. Capraro, M.M. Capraro, Using the engineering design process as the structure for project-based learning: an informal STEM activity on bridge-building, in: Proceedings of 2016 IEEE Integrated STEM Education Conference, ISEC), 2016, pp. 249–256.

[39] C. Barris, L. Torres, E. Simon, Learning based on the project entitled "Design and construction of a wooden bridge", J. Technol. Sci. Educ. 6 (2) (2016) 135–143, https://doi.org/10.3926/jotse.219.

[40] Y. Zhao, Design and Practice Research of Science Project-based Activities under STEM Concept in Primary School, Dissertation of Hebei University, 2018, pp. 28–31 (in Chinese).

[41] J.A. Colliver, Effectiveness of problem-based learning curricula: research and theory, Acad. Med. 75 (3) (2000) 259–266, https://doi.org/10.1097/00001888-200003000-00017.

[42] G.R. Norman, H.G. Schmidt, The psychological basis of PBL. A review of the evidence, Acad. Med. 67 (9) (1992) 557–565.

[43] F. Dochy, M. Segers, P. Bossche van den, D. Gijbels, Effects of problem-based learning: a meta-analysis, Learn. InStruct. 13 (5) (2003) 533–568, https://doi.org/10.1016/S0959-4752(02)00025-7.

[44] Y. Lin, Discussion on application of project teaching method in general technology teaching - taking "Load bearing design of paper bridge" project as an example, Educational Research in Fujian: Basic Educ. 3 (2014) 17–19 (In Chinese).

[45] E.J. Chikofsky, J.H. Cross, Reverse engineering and design recovery: a taxonomy, IEEE Software 7 (1) (1990) 13–17, https://doi.org/10.1109/52.43044.

[46] M.G. Rekoff, On reverse engineering, IEEE Transactions on Systems, Man, and Cybernetics 15 (2) (1985) 244–252, https://doi.org/10.1109/TSMC.1985.6313354.

[47] B.C. Behrens, R.R. Levary, Practical legal aspects of software reverse engineering, Commun. ACM 41 (2) (1998) 27–29.

[48] R.J. Abella, J.M. Daschbach, R.J. McNichols, Reverse engineering industrial applications, Comput. Ind. Eng. 26 (2) (1994) 381–385, https://doi.org/10.1016/0360-8352(94)90071-X.

[49] K. Huang, Enhancing design education by product reverse engineering, in: Proceedings of the Canadian Design Engineering Network (CDEN) Conference, Canadian Engineering Education Association, 2008, pp. 1–11, https://doi.org/10.24908/pceea.v0i0.3742.

[50] K.N. Otto, K.L. Wood, Product evolution: a reverse engineering and redesign methodology, Res. Eng. Des. 10 (4) (1998) 226–243, https://doi.org/10.1007/s001639870003.

[51] K.L. Guthrie, H. McCracken, Reflection: the importance of making meaning in e-service-learning courses, J. Comput. High Educ. 26 (3) (2014) 238–252, https://doi.org/10.1007/s12528-014-9087-9.

[52] M. Ogot, G. Kremer, Developing a framework for disassemble/assemble/analyze (DAA) activities in engineering education, in: Proceedings of 2002 ASEE Annual Conference, Canada, Montreal, 2006, pp. 1–10, https://doi.org/10.18260/1-2–1103.

[53] D. Moore-Russo, K. Grantham, K. Lewis, S.M. Bateman, Comparing physical and cyber-enhanced product dissection: analysis from multiple perspectives, Int. J. Eng. Educ. 26 (6) (2010) 1378, https://doi.org/10.1115/DETC2010-28350.

[54] B. Zhong, X. Liu, L. Xia, W. Sun, A proposed taxonomy of teaching models in STEM education: robotics as an example, Sage Open 12 (2) (2022) 1–15.

[55] R.E. Barr, P.S. Schmidt, T.J. Krueger, C. Twu, An introduction to engineering through an integrated reverse engineering and design graphics project, J. Eng. Educ. 89 (4) (2000) 413–418, https://doi.org/10.1002/j.2168-9830.2000.tb00545.x.

[56] M. Akerdad, A. Aboutajeddine, M. Elmajdoubi, Supporting Product Development Activities by Reverse Engineering Technique, Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management Detroit, Michigan, USA, 2020.

[57] G.L.E. Okudan, S. Mohammed, An investigation on the students' perception of dissection effectiveness in a redesign context, in: Proceedings of 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2008, pp. 395–401, https://doi.org/10.1115/DETC2008-50125.

[58] H.U.G.O. Elizalde, I.R. Solorio, Y. Perez, R.M. Menéndez, P. Orta, D. Guerra, R.A. Ramirez, An educational framework based on collaborative reverse engineering and active learning: a case study, Int. J. Eng. Educ. 24 (6) (2008) 1062–1070.

[59] B. Zhong, T. Li, Can pair learning improve students' troubleshooting performance in robotics education? J. Educ. Comput. Res. 58 (1) (2020) 220–248.

[60] J. Sweller, J.J. Van Merrienboer, F.G. Paas, Cognitive architecture and instructional design, Educ. Psychol. Rev. 10 (3) (1998) 251–296, https://doi.org/10.1023/A:1022193728205.

[61] F. Paas, J.E. Tuovinen, H. Tabbers, P.W. Van Gerven, Cognitive load measurement as a means to advance cognitive load theory, Educ. Psychol. 38 (1) (2003) 63–71, https://doi.org/10.1207/S15326985EP3801_8.

[62] C. Bishop-Clark, J. Courte, E.V. Howard, Programming in pairs with Alice to improve confidence, enjoyment, and achievement, J. Educ. Comput. Res. 34 (2) (2006) 213–228, https://doi.org/10.2190/CFKF-UGGC-JG1Q-7T40.

[63] J.A. Fredricks, P.C. Blumenfeld, A.H. Paris, School engagement: potential of the concept, state of the evidence, Rev. Educ. Res. 74 (1) (2004) 59–109, https://doi.org/10.3102/003465430740010.

[64] D. Mutlu-Bayraktar, V. Cosgun, T. Altan, Cognitive load in multimedia learning environments: a systematic review, Comput. Educ. 141 (2019) 103618, https://doi.org/10.1016/j.compedu.2019.103618.

[65] B. Zhong, Y. Wang, Effects of roles assignment and learning styles on pair learning in robotics education, Int. J. Technol. Des. Educ. 31 (1) (2021) 41–59.

[66] J.C.Y. Sun, R. Rueda, Situational interest, computer self-efficacy and self-regulation: their impact on student engagement in distance education, Br. J. Educ. Technol. 43 (2) (2012) 191–204, https://doi.org/10.1111/j.1467-8535.2010.01157.x.

[67] B. Zhong, Q. Si, Troubleshooting to learn via scaffolds: effect on students' ability and cognitive load in a robotics course, J. Educ. Comput. Res. 59 (1) (2021) 95–118.

[68] B. Carlson, P. Schoch, M. Kalsher, B. Racicot, A motivational first-year electronics lab course, J. Eng. Educ. 86 (4) (1997) 357–362, https://doi.org/10.1002/j.2168-9830.1997.tb00309.x.

[69] T. Flowerday, G. Schraw, J. Stevens, The role of choice and interest in reader engagement, J. Exp. Educ. 72 (2) (2004) 93–114, https://doi.org/10.3200/JEXE.72.2.93-114.

[70] C. Toh, S. Miller, G.E.O. Kremer, The role of personality and team-based product dissection on fixation effects, Advances in Engineering Education 3 (4) (2013) 1–23.

[71] B.M. Capobianco, J. DeLisi, J. Radloff, Characterizing elementary teachers' enactment of high-leverage practices through engineering design-based science instruction, Sci. Educ. 102 (2) (2018) 342–376, https://doi.org/10.1002/sce.21325.

[72] C.M. Cunningham, G.J. Kelly, Epistemic practices of engineering for education, Sci. Educ. 101 (3) (2017) 486–505, https://doi.org/10.1002/sce.21271.

[73] Y. Ding, D. Ceglarek, J. Shi, Design evaluation of multi-station assembly processes by using state space approach, ASME Journal of Mechanical Design 124 (3) (2002) 408–418, https://doi.org/10.1115/1.1485744.

[74] B. Hu, Y. Zhao, Creative self-efficacy mediates the relationship between knowledge sharing and employee innovation, Social Behavior and Personality, Int. J. 44 (5) (2016) 815–826, https://doi.org/10.2224/sbp.2016.44.5.815.