Develop and validate STEM education activities using the "6E Design Teaching Model": Taking "Dynamics and Energy Conversion in Sail Car Design" as an example

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Abstract: This study employed a mixed research approach to analyze commonly used teaching models in STEM education and integrated the findings of comprehensive STEM research. The 6E Design Teaching Model (Engage, Explore, Explain, Engineer, Enrich and Evaluate) was selected, following the "Science-Technology-Engineering-Mathematics integration" approach. It was used to develop STEM education activities targeting students in the 5th and 6th grades, focusing on "Dynamics and Energy Conversion in Sail Car Design." Through three rounds, the effectiveness and feasibility of the activities were examined. The study employed quantitative tools and qualitative interviews (including teachers and students) to improve the teaching process and instructional framework. The results indicate that (1) STEM education activities developed using the 6E Model significantly enhance students' interest in engineering subjects when applied in teaching practice; (2) the instructional activities can effectively be applied in classrooms that integrate scientific inquiry and engineering practices. Over the course of the three rounds, the participating teachers demonstrated improved classroom control and time management, while student scores in engineering design projects showed noticeable progress. Through the optimization of the teaching process, instructional framework, and other aspects such as materials, operations and management, the study ultimately developed a highly practical STEM education case that integrates engineering practices into science inquiry classrooms. This case serves as a reference for frontline science teachers and researchers.

Keywords: 6E Design Teaching Model, Integrated STEM Education, Activity Design

1. Introduction

STEM education (Science, Technology, Engineering and Mathematics) is an important means to cultivate students' innovation and practical abilities. Although researchers have different understandings and perspectives on the concept, connotation and characteristics of STEM education(Hubelbank & Oliva, 2014; Mersin National Education Directorate, Turkey & Uygur, 2022), they all point to the common goal of interdisciplinary integration, with a broader and wider scope of integration(Radloff & Guzey, 2016). Various studies have shown that among the four disciplines of S, T, E and M, mathematics and science are the primary subjects, while others serve as connecting links, resulting in the marginalization of the engineering discipline. In recent years, many countries have implemented engineering education reforms in K-12 (kindergarten through twelfth grade) schools(Moore et al., 2014; National Research Council, 2009). For example, a report titled "Preparing and Inspiring the Future STEM Workforce of America: K-12 Science, Technology, Engineering and Mathematics (STEM)" submitted to the President of the United States emphasized the need to cultivate students with a strong STEM background to remain competitive in the global society(National Research Council, 2011). Integrating scientific inquiry and engineering practices into science classrooms to form Integrated/Integrative STEM Education has become one of the important trends in the development of STEM education worldwide (Guzey et al., 2016). Therefore, our research will follow six steps (see Figure1).

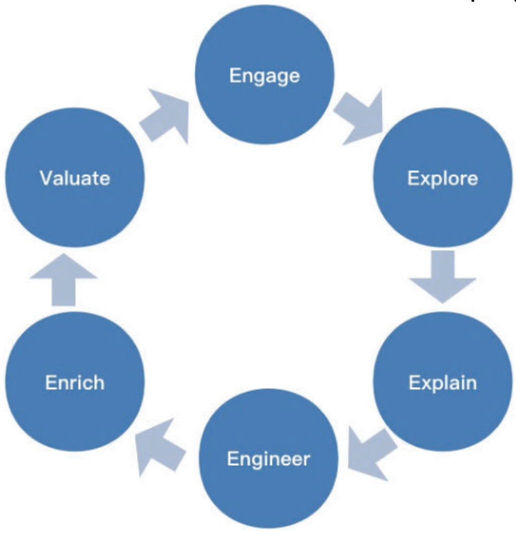

Figure1. 6E Design Teaching Model (the 6E Model)

Researchers divided the overall framework of integrated STEM education into four components: goals, outcomes, nature and scope of integration and implementation(National Research Council, 2014). This study adopts an integrated approach based on scientific exploration and engineering design, to stimulate students' interest in exploration, encourage them to design and create engineering projects and apply interdisciplinary knowledge.

The 5E teaching model was developed by the Biological Sciences Curriculum Study (BSCS) in the 1980s in the United States based on the constructivist learning perspective for scientific inquiry. It includes five stages: engagement, exploration, explanation, elaboration, and evaluation to form an understanding of scientific concepts. It has been widely used in biology, physics, chemistry, science and out-of-school science education activities(Duran & Duran, 2004). Barry (2014) proposed adding an “engineering” stage to the 5E teaching model, resulting in the 6E Model: Engage, Explore, Explain, Engineer, Enrich and Evaluate. Engage aims to stimulate interest and enhance learning participation, explore provides opportunities for constructing self-knowledge, understanding analysis and hands-on operation, explain provides opportunities for reflection, explanation, modification and elaboration of knowledge, engineer provides opportunities to apply learned knowledge and technology to practice, enrich promotes in-depth exploration of knowledge and evaluate checks and evaluates learning outcomes.

Khaeroningtyas et al. (2016) developed a STEM education activity with the theme of “Temperature and Its Changes” using the 6E Model. They implemented a quasi-experimental design and found that the experimental group achieved higher scores in the topic of temperature and its changes. Lai & Chu (2017) utilized the 6E Model to develop a STEM education activity with the theme of “Quadcopter Assembly”. The learning performance of 48 middle school students showed significant improvement. Hsiao et al. (2022) implemented a quasi-experimental design found that using robot-based practices to develop an activity that incorporated the 6E model can improve elementary school students’ learning motivation, learning performance, computational thinking ability, and hands-on ability. The STEAM education activities, using the 6E Model, were implemented with third-grade students in Thailand. After 12 class hours, the students found improvements in academic performance, scientific creativity, and innovation abilities(Jongluecha & Worapun, 2022). And the 6E Model in a practical activity involving the design of egg protection devices was found to have a positive impact on the technological attitude and technological inquiry abilities of the participating secondary school students(Lin et al., 2020).

Two study hypotheses were proposed: utilizing the 6E Model to develop STEM education activities can be effectively applied in teaching practice and STEM education activities developed using the 6E Model can enhance students' interest in engineering learning. This study employed the 6E Model to develop and design integrated STEM education activities and validated their effectiveness through implementation, resulting in a curriculum design method of practical significance.

2. Method

Data was collected using quantitative tools and qualitative interview methods. Quantitative data included scores of students' engineering design projects and surveys on their interest in engineering and science subjects. Qualitative data included interviews with teachers and students. The research process is as follows (see Figure 2).

2.1 Participant

This study recruited participants through collaboration with one university community, a tutoring organization and a parents' group. A total of 56 students (15 in 5th grade, 40 in 6th grade) and one teacher who was a science education instructor from the tutoring organization.

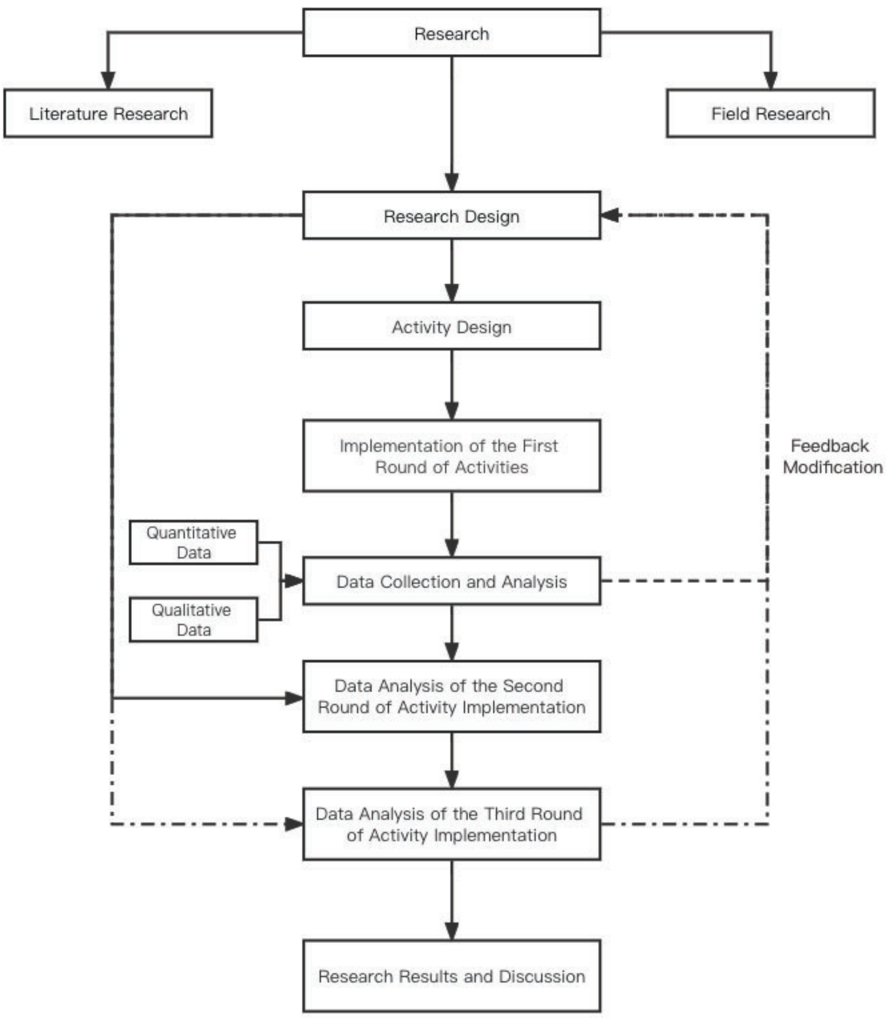

Figure 1. Research Process Flowchart

2.2 Research Tools

2.2.1 The STEM Interest Survey

The STEM Interest Survey is an 25-item self-report scale with 5 factors of interesting in science, technology, mathematics, engineering and STEM careers (Tyler-Wood et al., 2010). Items were answered on a 7-point Likert scale that ranges from 1 (not at all important) to 7 (extremely important). The Cronbach's Alpha is between 0.84 and 0.93.

2.2.2 Student Work Scoring Sheet

The the Performance-Based Evaluation(PBE) are four factors of completion, feasibility, aesthetics and innovation (Jin et al., 2015). The PBE uses a 4-point scale (1-4), with high stability and reliability.

2.2.3 Interview Outlines

The study includes interviews with teachers and students. Teacher interviews primarily focus on the situations and issues encountered during actual teaching processes, covering topics such as teaching methods and evaluation methods. For example, do you consider this teaching method to be similar or different from previous methods? What are the advantages and disadvantages? Student interviews aim to explore the application of scientific principles and mathematical knowledge in engineering practices during the activity, as well as the difficulties encountered in the classroom and overall satisfaction with the course activities. For example, what difficulties did you encounter during the learning process? For example, abstract concepts or challenging hands-on operations. Please provide specific examples.

3. Research Steps

3.1 Development of Teaching Activities

In the development of the 6E Model, five aspects were considered: needs analysis, content design, teaching resources, process design and evaluation of outcomes. The needs analysis involved analyzing educational resources and learners. The study adopted classroom-based activities with a relatively short duration and low resource requirements. Fifth and sixth-grade students were chosen over third and fourth-grade students due to their higher levels of self-management skills, hands-on practical abilities and proficiency in mathematical operations and independent thinking.

Content design involved conducting surveys among frontline teachers and curriculum design engineers, followed by preliminary analysis of potential themes. Ultimately, ancient Chinese transportation vehicles, specifically the sail-powered cart, were selected as the theme for the curriculum design.

Teaching resources included the development of teaching handbooks, student handbooks and activity materials kits. The teaching handbook guided teachers in understanding the curriculum design concepts, teaching processes and lesson preparation. The student handbook helped students plan their learning activities, record important course information, and reflect on their experiments. The materials kit bundled together all the materials used in the curriculum and was distributed to the students. The process design stage consisted of the following phases: engage, explore, explain, engineer, enrich and evaluate. Outcome assessments included measuring in student interest in engineering learning, grading engineering design projects and interviewing teacher and students.

3.2 Implementation of teaching activities

A total of three rounds of courses were conducted, with one round per week, lasting 120-180 minutes each time. After each round of courses, the researchers conducted statistical analysis on the data and conducted interviews with the teachers and students for further improvement. The detailed process of the first round of courses is as follows (see Table 1).

Table 1. *The Detailed Process*

Phase	Time(mins)	Detailed
Engage	20-30	Teacher's explanation and student discussions enable students to learn about the history of sailboats and the science and applications of sail design.
Explore	20-30	Students participate in a sailboat-making competition, followed by sharing their creations, after which the teacher provides explanations of the underlying principles, such as friction and material selection.
Engineering	20-40	Students redesign their sailboats, with the teacher introducing the concepts of engineering and guiding them through the engineering design process to optimize their designs.
Enrich	40-50	Students work in groups of four to collaboratively design and build sailboats for a competition.
Evaluation	20-30	The teacher provides feedback and students share their experiences, with the teacher concluding the activity with a summary.

3.2.1 Improvement of Teaching Process

In the second round of activities, the engage was conducted by group teaching. The topic focused on common tools that utilize wind energy and interactive discussions were held with the students to introduce the concept of harnessing wind energy. In the exploration phase, the straws were replaced with a more rigid and easily fixable material and the structure-building component was simplified to using foam boards for support. The explanation replaced the traditional lecture-style delivery of key points with interactive mini-games. The teacher used the physical model of the cart to ask questions and engage the students in discussions while recording their responses. In the engineering, more time was allocated for teacher explanations and student hands-on activities. During the enrich, students formed teams of four to participate in a competition. In the evaluation, each student conducted a brief analysis.

After optimizing these changes, the subsequent recruitment and classes were conducted, and the teachers were able to smoothly control the classroom. The teaching experience improved and there was an increase in the completion rate of student projects.

3.2.2 Improvement of Teaching Framework

After the first round of activities, exploration and engineering components have been added to provide reference experimental procedures for students who may encounter difficulties in certain operations (More see appendix1, appendix2). With the inclusion of experimental procedures, in the second round of activities, over 50% of students successfully completed 60% or more of the content and design of their projects, as outlined in the learning manual. For the third round of activities, the SCAMPER(Substitute, Combine, Adapt, Modify/Magnify, Purpose, Eliminate and Rearrange/Reverse) brainstorming cognitive tool was used to guide students through the problem-solving process(Serrat & Serrat, 2017). Additionally, the researchers employed the 3-2-1 Quick Assessment Method (3-2-1) commonly used in the 5E inquiry-based teaching model, to encourage students to share three takeaways, two challenges and one aspect they found particularly effective during the entire activity.

Following these improvements, the success rate of student exploration experiments and the completion level of their projects significantly increased in the third round of instruction.

3.2.3 Other Improvements

Firstly, in terms of personnel coordination, there was enhanced communication among researchers, recruitment personnel and teachers. The recruitment process was coordinated and planned to avoid blind enrollment. Secondly, in terms of course materials, canvas, thinner wood, and additional small wooden sticks were added to meet the students' needs and enthusiasm for fabrication and design.

With these improvements, the recruitment of students became more targeted, avoiding the interference of ineffective samples. The use of additional materials by students led to more refined and complex design projects, resulting in improved performance during testing.

4. Analysis of STEM Learning Interest

4.1 STEM Learning Interest Analysis Results

Through three rounds of recruitment and course implementation, a total of 27 valid STEM interest survey forms were collected (6 forms in the first round, 10 forms in the second round and 11 forms in the third round). The analysis results are as follows (see Table 2).

Table 2. *STEM Learning Interest Analysis Results*

		Science	Math	Technology	Engineering	STEM Career Interests
First round	M	1.00	1.50	7.67	0.17	1.00
	df	5.00	5.00	5.00	5.00	5.00
	t	1.94	1.31	4.97	0.54	1.23
	P	0.11	0.25	0.004*	0.61	0.28
Second round	M	0.27	1.36	3.09	0.00	0.27
	df	9.00	9.00	9.00	9.00	9.00
	t	0.40	1.04	3.40	0.00	0.39
	P	0.70	0.33	0.007*	1.00	0.71
Third round	M	1.50	0.70	5.60	0.50	0.60
	df	10.00	10.00	10.00	10.00	10.00
	t	2.24	0.90	3.89	0.92	2.25
	P	0.05	0.39	0.004*	0.38	0.05

It can be observed that there were no significant differences in students' interest in science, technology, mathematics, and STEM careers. However, there was a significant difference in engineering learning interest after instructional intervention.

4.2 Analysis Results of Engineering Design Project

The research conducted a scoring and recording of the engineering design projects in each round. There were 24 projects in the first round, 19 projects in the second round and 12 projects in the third round. In each round, the final scores for each dimension of the projects were calculated as the average scores. The analysis focused on comparing whether there was an improvement in the scores of student projects in terms of completeness, feasibility, aesthetics and innovation (see Figure 3.).

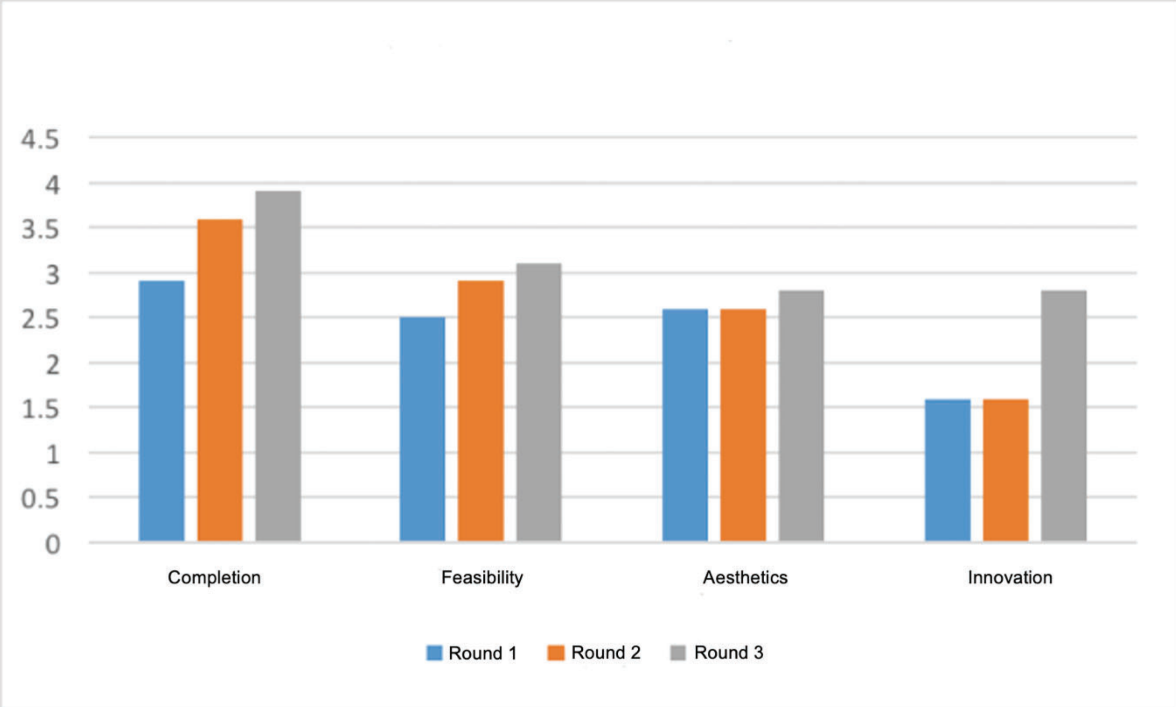

Figure 2. Analysis Results of Engineering Design Project

During the three rounds, there was an improvement in the completeness, feasibility and innovation of student engineering design projects. The aesthetics also showed improvement in the third round, although the difference was not significant. Moreover, there was a noticeable improvement in the completeness between the first and second rounds and the innovation significantly improved after the second round (More see appendix3, appendix4, appendix5).

4.3 Interview analysis results

From an overall perspective, after the first round of the activities, students who were interviewed (both those who successfully completed the engineering design projects and those who did not) could only recall the data mentioned by the teacher in class and provide a simple explanation without being able to articulate how to apply it to the design of the sail car. However, in the second and third rounds, some students were able to assess and evaluate relevant engineering knowledge and concepts. In the third round, some students even proposed incorporating knowledge of buoyancy to make the sail car amphibious. Furthermore, in terms of satisfaction with the course and interest in the activities, apart from some students in the first round expressing a shortage of materials, overall satisfaction was high.

5. Discussion

The suggestions and improvement ideas you have provided are intended for frontline teachers and external science educators to consider. Firstly, you recommend making thorough preparations when implementing activities using the 6E Model. In the engage, you can organize the curriculum around real-life engineering problems that need solving and design inquiry experiments with moderate difficulty to provide necessary scaffolding for students, thereby stimulating their confidence in hands-on design. In the explanation, teachers can conduct inquiry experiments, explain in detail the scientific concepts, principles and core knowledge required to solve engineering problems by referring to relevant materials (including interdisciplinary subjects such as science history, technological development, social sciences, mathematics, etc.). During the engineering, teachers can explain the concepts and design processes involved in engineering and utilize creative thinking tools like SCAMPER brainstorming to assist students in organizing and conceptualizing their design ideas. Furthermore, teachers should personally test and create the products that students are expected to make in class, engage in iterative testing and provide timely feedback and suggestions. In the evaluation phase, employ diverse assessment methods, avoid solely teacher-led evaluation and consider using tools such as the 3-2-1 to allow students to share their three takeaways, two questions and one positive aspect, enabling them to reflect on their learning outcomes and summarize the course content. Secondly, you emphasize the importance of teamwork and collaboration in the implementation process to enhance work efficiency and prevent errors. For example, in the case of the small sail car activity, the teaching instructor's expertise in physics and engineering knowledge, along with their extensive teaching experience, greatly aided the researcher in improving the instructional design.

Additionally, you highlight the challenges encountered during the implementation, including difficulties in student recruitment and limitations concerning experimental materials, tools, and facilities. Teachers may allocate a significant portion of their teaching time to maintain order during the process of students' hands-on construction, which results in less time dedicated to explaining the instructional content. You suggest that this issue may arise from insufficient consideration of the actual teaching situation and potential problems during the initial research phase. Therefore, when designing activities with engineering themes, you recommend that teachers pay attention to preparatory work, such as collecting materials, conducting model testing, evaluating effects, and providing abundant instructional scaffolding to maintain students' confidence in autonomous design.

6. Conclusion

Based on the research findings and experiences integrating comprehensive STEM education with K-12 engineering education, an exploration of incorporating engineering elements into science classrooms was conducted. A STEM education case study was designed and developed with a focus on the design of an ancient Chinese transportation vehicle called the sail car. It was discovered that when STEM education activities developed using the 6E Model were applied in teaching practices, they significantly enhanced students' interest in the field of engineering. The instructional activities proved effective for integrating scientific inquiry with engineering practices in the classroom. Through optimizing the teaching process, instructional scaffolding and other aspects such as materials and operations management, a highly practical STEM education case that integrates engineering practices into science inquiry classrooms was developed, offering a new approach for international STEM education curriculum development.

7. Prospects

The limitations of the study include focusing only on mechanics and “technology and engineering” themes without forming a complete series of courses, a small sample size and a single evaluation method. In future research, the enrichment could be expanded by incorporating the use of digital tools to guide students in adding sensors and data analysis tools that provide real-time monitoring and display of the car's motion status to the existing sail car model. In terms of curriculum topics, organizing instructional content around technology and engineering or broader themes could be considered to develop a series of courses.

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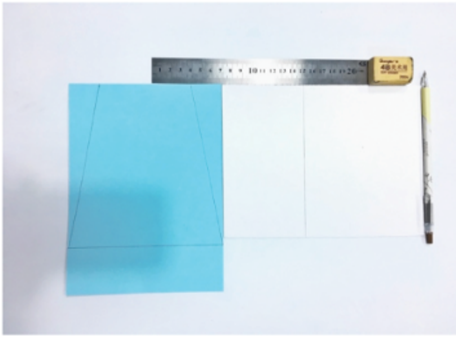
Appendix

Appendix 1. Explore (added)

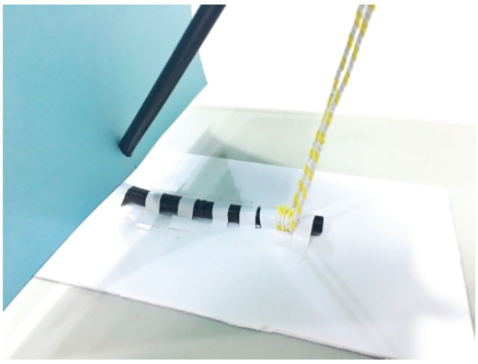
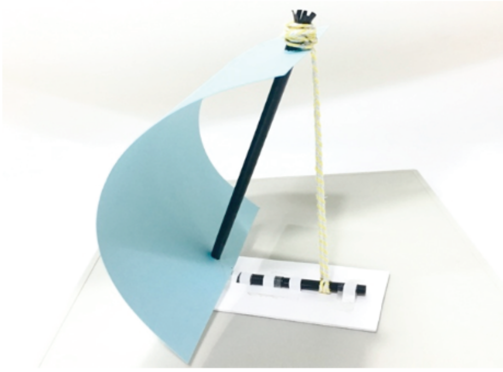
1. Cut the sail and base with precision.



2. Use a carving knife to create two holes of straw size on the top and bottom of the sail, and connect the straw with the sail.

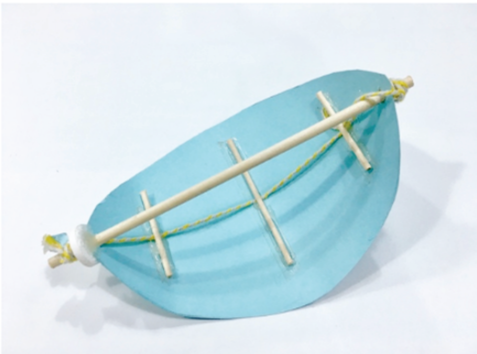
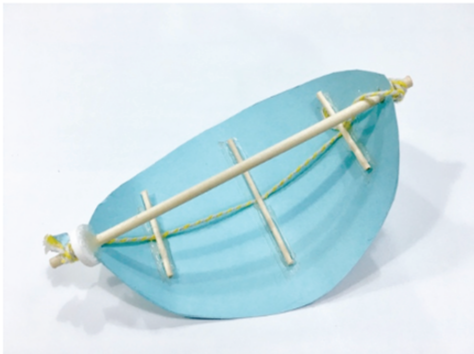
3. Secure the straw on the cut-out foam board base with double-sided tape and nylon rope.

4. Reinforce the base and straw with double-sided tape. Voila! You now have a model that runs with just one breath.

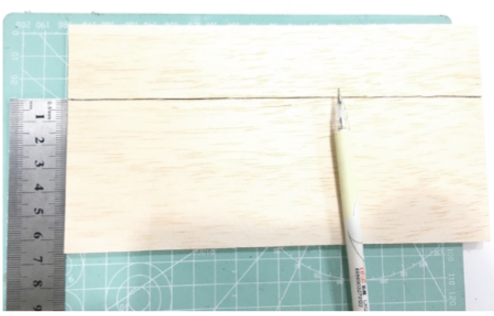
 

Appendix 2. Engineering (add)

1. Strengthen and refine the design of the sail, connecting it to the mast and a base with small holes.

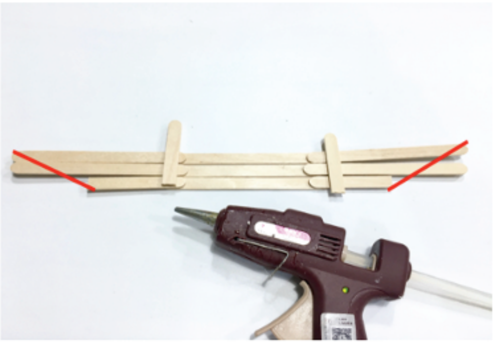
 

2. Measure a rectangle on a wooden board with dimensions of 20cm length and 60cm width for the sail car base.

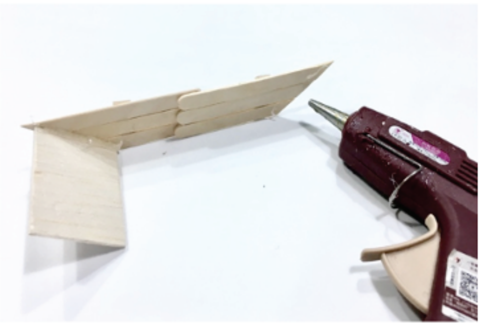
 

Cut it open with a saw following the guidelines. Sawing can be done by placing the board on the edge of a table, exposing a small portion of it, using one hand to press one side onto the table, and tilting the saw with the other hand to saw it back and forth.
3. Use a hot glue gun to attach three popsicle sticks into one long stick, then divide it into two segments of 3.5cm each and connect three sticks together.

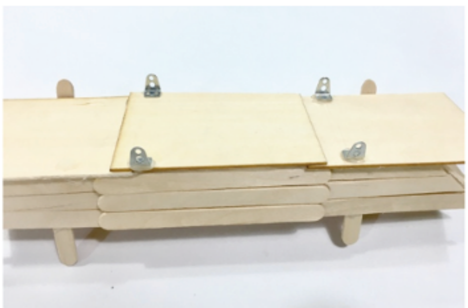
4. Draw an isosceles trapezoid on both sides of the wood stick and cut off the excess with scissors. Repeat the same process to make another isosceles trapezoid of the same size and shape.



5. Use a hot glue gun to attach the sawed base to the trapezoid side of the sail car.



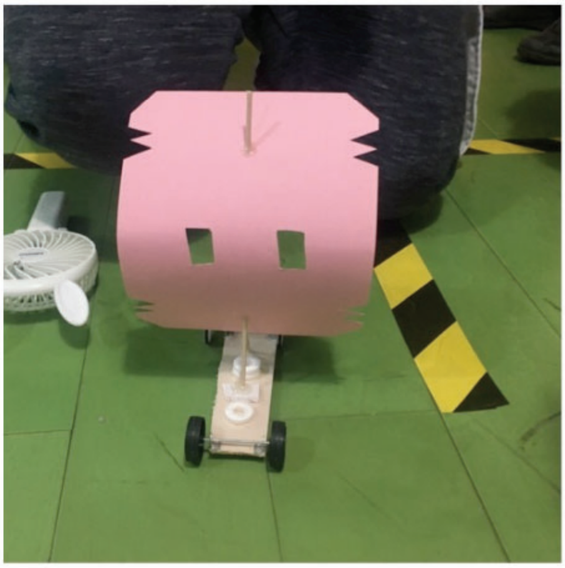
6. Use a hot glue gun to connect the triangle iron to the bottom of the car, and assemble the axle and wheels.

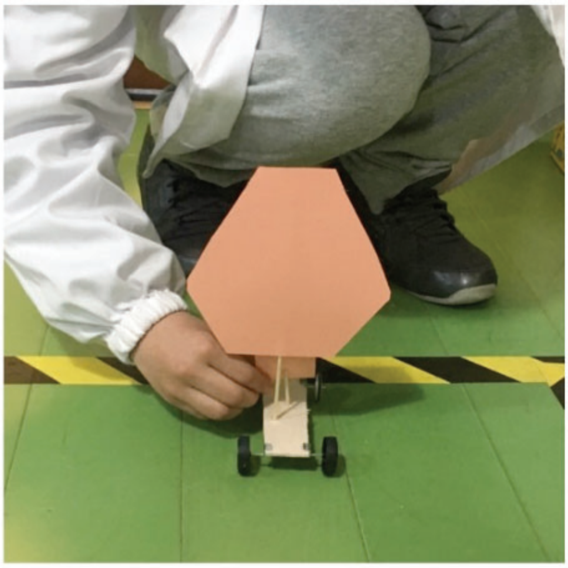


7. Secure the base of the sail on the front of the sail car using a hot glue gun.

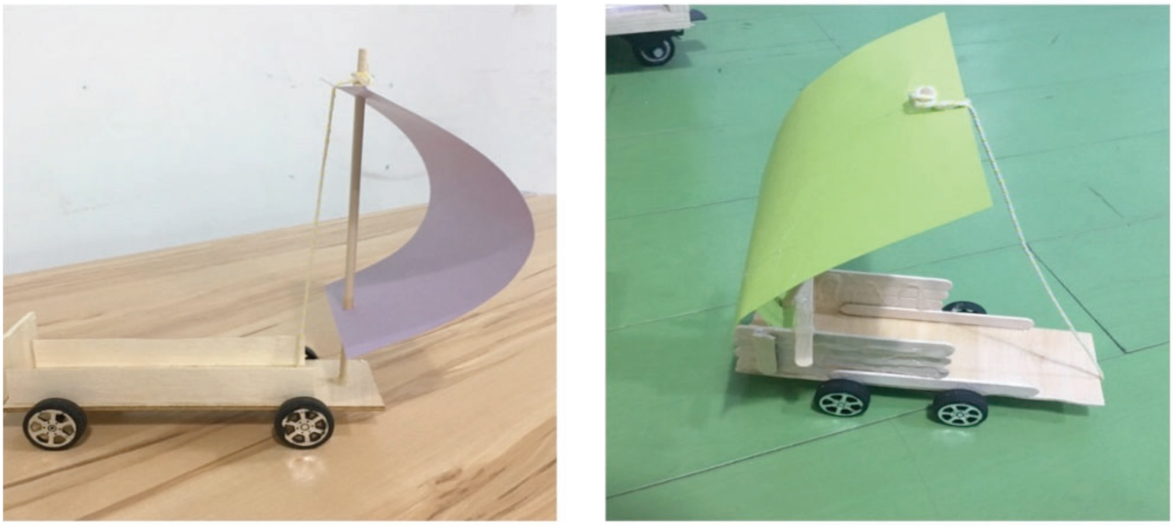
8. The sail car is now complete. Design a logo and embellish it beautifully in preparation for a mineral water racing competition.

Appendix 3. The first round of student works (partial)





Appendix 4. The second round of student works (partial)



Appendix 5. The third round of student works (partial)