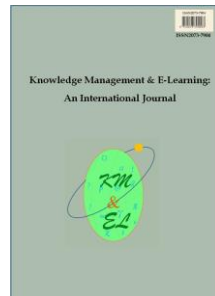

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Integrated STEM curriculum design: A conceptual framework and visible thinking approach

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Abstract: Integrated STEM education has been widely promoted to cultivate students' competencies to solve real-world problems. To promote STEM education, it is crucial to design high-quality STEM curricula. However, STEM curriculum design is a complex task involving multiple components and complicated processes to coordinate the components into a coherent design. Existing STEM teacher training programs lack sufficient guidance on how to deal with the complexity in STEM curriculum design, posing challenges to STEM teachers. To address the gap, this study proposed a conceptual framework that visualizes the complex process of STEM curriculum design. The conceptual framework includes (a) a process model for STEM curriculum design, with key strategies and guidelines for each step, and (b) a scaffold for designing STEM teaching and learning activities. An example is presented for illustration. Using the proposed approach, a training program on STEM curriculum design was provided to 27 pre-service teachers. After the training, the participants made a significant improvement in their STEM curriculum design performance, especially in the design of teaching and learning activities. Participants' comments highlight the benefits of the proposed approach, in particular its provision of a systematic framework and clear guidelines for STEM curriculum design. The study demonstrates the feasibility and promising potential of the visible thinking approach in supporting teacher learning of integrated STEM curriculum design.

Keywords: Integrated STEM education; Curriculum design; Conceptual framework; Teacher education; Visible thinking

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1. Introduction

Integrated STEM education, the integration of science, technology, engineering, and mathematics (STEM) into a joint learning experience, has been globally promoted and demonstrated promising impacts on student learning (Chen et al., 2025). It focuses on cultivating students' competencies to address real-world problems and global challenges (e.g., climate change, resource shortage, environmental pollution, and health) by applying connected knowledge to solve problems. Different from traditional STEM education employing teacher-centred and knowledge-oriented lectures to teach individual STEM subjects, integrated STEM education has four core characteristics: (a) integrating subject content across multiple disciplines of STEM and beyond; (b) connecting abstract knowledge to real-world problems; (c) engaging students in authentic practice mainly through inquiry- or design-based tasks; and (d) enabling students to play an active role in learning (Brown et al., 1989; Chen et al., 2025; Kelley & Knowles, 2016; Roehrig et al., 2021; Thibaut et al., 2018). A number of empirical studies have proven the benefits of integrated STEM education on acquiring subject knowledge (Knezek & Christensen, 2020; Lin et al., 2019), developing higher-order thinking skills (Al-Mughrabi et al., 2025; Korur et al., 2017), promoting problem-solving performance (Lin et al., 2019; Fan & Yu, 2017; Wu et al., 2023; Wu & Wang, 2012), and facilitating STEM learning interest, motivations, and self-efficacy (Lamb et al., 2015).

To fulfil the advantages of STEM education, it's very important to design high-quality integrated STEM curricula. Existing teacher training programs on STEM curriculum design have focused on offering lectures (Kim & Bolger, 2017), encouraging teachers to read and reflect on curriculum design examples (Williams et al., 2019), asking teachers to design and implement STEM curricula (Berisha & Vula, 2024; Guzey et al., 2016), and engaging teachers in STEM learning experiences as students (Milner-Bolotin, 2018; Quigley & Herro, 2016). These efforts show their benefits in developing teachers' understanding, motivations, and positive beliefs regarding integrated STEM curriculum design (Berisha & Vula, 2024; Quigley & Herro, 2016; Wang et al., 2020). However, they have minimal impact on improving teachers' capability to design quality STEM curricula by integrating knowledge from multiple disciplines and connecting abstract knowledge to real-world problems (Dare, 2019; Dong et al., 2020) or by designing effective and appropriate teaching and learning activities for learning with authentic problems (Guzey et al., 2016; Kim & Bolger, 2017; Maiorca & Mohr-Schroeder, 2020). As a result, many teachers have low self-efficacy and high anxiety about STEM curriculum design, and have doubts about the value and feasibility of integrated STEM education (Lesseig et al., 2016; Margot & Kettler, 2019).

The above problems can be attributed to the complexity of STEM curriculum design and a lack of sufficient guidance on the complex process of STEM curriculum design. STEM curriculum design is inherently a complex task, containing multiple components and complicated processes to coordinate the components into a coherent design (Jonassen, 2008; Stanovich & Stanovich, 2003; Stevenson et al., 2024; Wang et al., 2025; Wu et al., 2019). Complex tasks may impose high cognitive demands on learners; without appropriate support, it is difficult for learners to engage in effective thinking and

learning and achieve desirable outcomes (van Merriënboer & Kirschner, 2018; Wang, 2024). Existing teacher training programs on STEM curriculum design provide insufficient guidance on how to deal with the complexity in STEM curriculum design.

To address the gap, this study proposed a conceptual framework as a visible thinking approach for integrated STEM curriculum design. Visible thinking approaches utilise visual representations (e.g., concept maps, cognitive maps, mind maps, process flows, systemic models) to externalize complex ideas and processes (Cox, 1999; Jonassen, 2003; Wang et al., 2017, 2018a). They have been increasingly explored to promote meaningful understanding and higher-order thinking in complex tasks such as science inquiry, clinical diagnosis, and computer programming (Chen et al., 2021; Peng et al., 2024; Sun et al., 2019; Toth et al., 2002; Wang et al., 2011, 2018b). This study proposed a conceptual framework that visualized the complex process of integrated STEM curriculum design. It includes (a) a process model for STEM curriculum design, with key strategies and guidelines for each step, and (b) a scaffold for designing STEM teaching and learning activities. Further, this study explored the use of this approach to support teacher learning of STEM curriculum design and examined the feasibility and effects of the approach.

The research questions (RQs) of the study include the following:

RQ1: How to support teacher learning of integrated STEM curriculum design through a visible thinking approach?

RQ2: Can pre-service teachers improve their STEM curriculum design performance after a training program using the proposed visible thinking approach?

RQ3: What are the participating teachers' comments on the proposed visible thinking approach?

2. A visible thinking approach for integrated STEM curriculum design

The visible thinking approach was designed based on the four-component instructional design (4C/ID) model, a framework for systematic learning with complex tasks (Van Merriënboer & Kirschner, 2018). In this model, learners are provided with a systematic approach to solving complex problem, which is characterized by specifying the phases a learner must go through to solve a complex problem or complete an authentic task, and providing the rules-of-thumb or heuristics that may help the learner to accomplish each phase. Our study incorporated the visible thinking approach by (a) externalizing the complex process of integrated STEM curriculum design in eight steps and (b) providing relevant strategies or guidelines for each step. The eight steps and relevant strategies were proposed based on general guidelines for curriculum design (Dick et al., 2015; Großmann & Krüger, 2023; Jacobs et al., 2008) and relevant studies on STEM education and curriculum (Gale et al., 2020; Moore et al., 2014). The visible thinking approach aims to make the complex and implicit process of integrated STEM curriculum design visible and accessible to STEM educators. The conceptual framework includes: (1) a process model for STEM curriculum design, with key strategies and guidelines for completing the process and (2) a scaffold for the design of STEM teaching and learning activities.

2.1. A process model for STEM curriculum design

The process of integrated STEM curriculum design is presented in Fig. 1. The design process includes eight steps in three stages. Stage 1 focuses on determining the learning

topic and objectives and analyzing target learners, which serves as the foundation for the curriculum design. Stage 2 focuses on the design of core components of the curriculum, including a learning task, learning content, teaching and learning materials, teaching and learning activities, and assessment methods. Stage 3 focuses on writing up the designed curriculum plan and reviewing the entire design to ensure consistencies among different components.

To facilitate the completion of the design process, the key strategies or guidelines for each step are outlined in Table 1.

Table 1

Key strategies and guidelines for each step

Step	Key strategies and guidelines
1. Determine the learning topic and learning objectives	• The learning topic is connected with real-world problems and relevant to students' experiences and interests. • The learning objectives involve the integration of knowledge from multiple disciplines, promotion of problem-solving skills, and (if possible) formation of appropriate attitudes towards the learning topic. • The learning topic is consistent with the curriculum standards.
2. Analyze target learners	• The analysis of learners should focus on their prior knowledge and skills.
3. Design a learning task	• The learning task should focus on investigating or solving real-world problems that are appropriate for the learners in terms of their prior knowledge and/or skills. • The task should be feasible to implement using accessible materials and resources. • The learning task should involve knowledge and skills from multiple STEM disciplines.
4. Determine learning content	• The learning content should involve knowledge-focused and task-focused learning points. • The knowledge-focused learning points can involve conceptual knowledge from multiple STEM disciplines and background knowledge for the task. • The task-focused learning points can consider inquiry or design skills, tool skills, and other skills (e.g., reading and drawing data graphs).
5. Prepare teaching and learning materials	• The teaching and learning materials cover both knowledge-focused and task-focused learning points.
6. Design teaching and learning activities	• See the scaffold for the design of STEM teaching and learning activities (Table 2).
7. Design assessments methods	• The assessment methods are consistent with the learning objectives. • Consider formative assessment in addition to tests.
8. Write up the curriculum plan	• Ensure consistencies among different components. • Make improvements based on practice and peer comments.

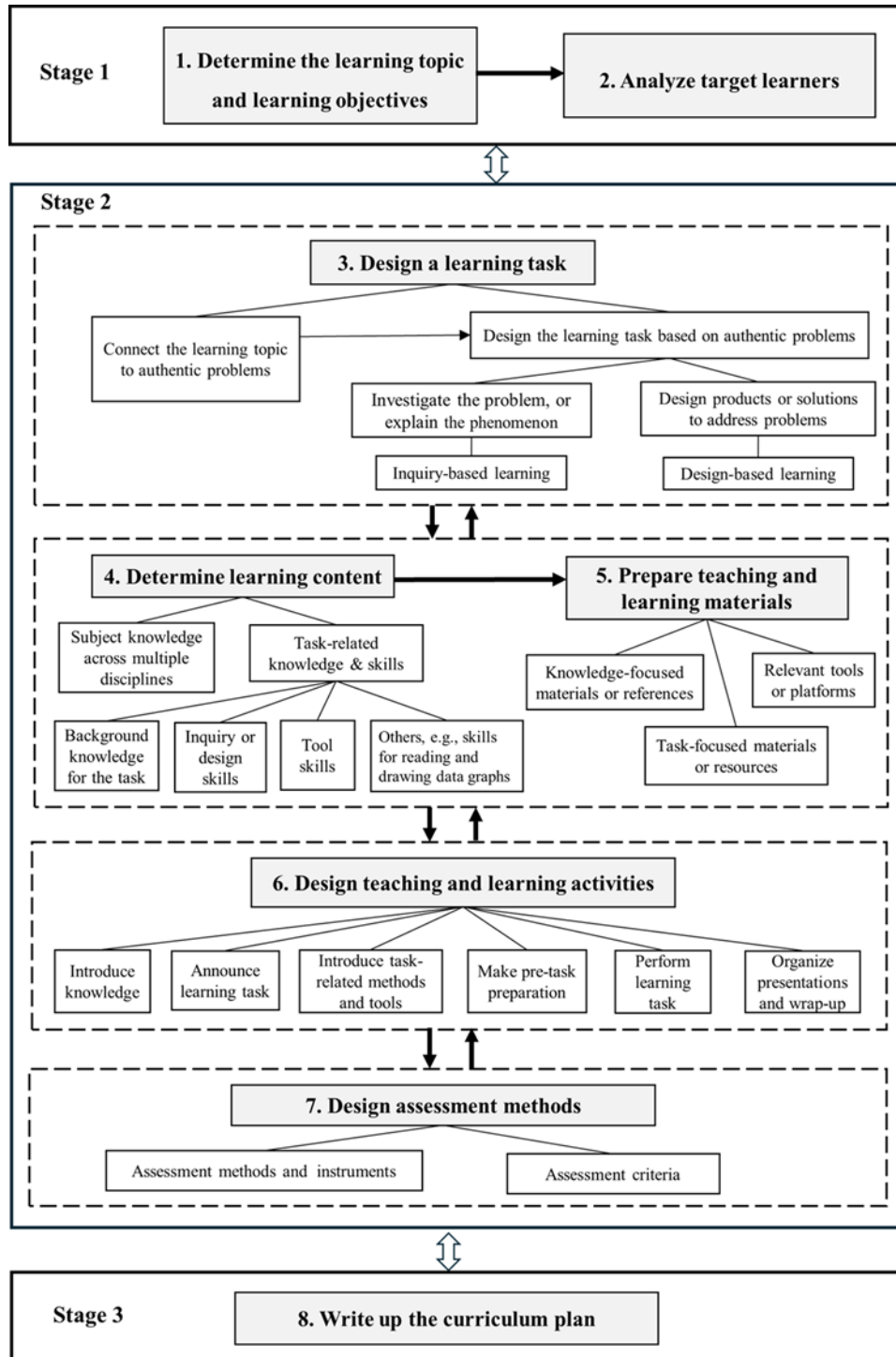


Fig. 1. A process model for STEM curriculum design

2.2. A scaffold for the design of STEM teaching and learning activities

The most challenging part of STEM curriculum design is the design of STEM teaching and learning activities, which involves a series of activities for students as well as for the teacher. This study proposed a scaffold for the design of STEM teaching and learning activities. As shown in Table 2, the scaffold presents a number of STEM teaching and learning activities to be performed by the teacher and students.

Table 2

A scaffold for the design of STEM teaching and learning activities

Phase	Teacher Activity	Learner Activity
Introduce knowledge	Teach/introduce task-related subject knowledge	Group discussion on subject knowledge
Announce learning task	Make the learning task explicit	Understand the learning task (e.g., What is to be investigated? What is to be designed?) Discuss and raise questions Discuss and raise questions
Introduce task-related methods and tools	Introduce task-related methods, such as: • Inquiry or design process or methods • Data analysis methods • Report writing techniques Introduce task-related tools and methods to use them, such as measuring tools and data analyzing tools.	
Make pre-task preparation (optional)	Provide scaffolding or feedback if needed	If needed, learners could design the experiment to test the hypotheses before implementation. If needed, learners could conduct place-based or online investigations to better understand the requirements for the learning task.
Perform learning task	Provide scaffolding or feedback if needed	Perform an inquiry-based task: • Form hypotheses • Test hypotheses through reasoning with collected evidence or through carrying out experiment, collecting data, and analysing data • Make conclusions Or, perform a design-based task: • Define requirements for designing products or solutions • Generate prototypes or solutions • Produce products or implement solutions • Test prototypes or solutions and gain testing results • Improve prototypes or solutions
Organize presentations and wrap-up	Organize learners to present their task outputs Provide feedback for learners	Present task outputs (e.g., inquiry results, designed products or solutions) If needed, learners could further improve their learning task performance based on self-reflection or feedback from the teacher or peers.

2.3. An example of STEM curriculum design using the proposed approach

This section presents an example to illustrate the proposed visible thinking approach for integrated STEM curriculum design. The designed curriculum is presented in Fig. 2, and the design process is described in the following sections.

Page 1

STEM Curriculum Titles Design eco-friendly lighting schemes for school courtyard	
Grade Seventh grade (the second year of secondary school)	
Teaching time About 5 class hours, depending on the implementing situation.	
Learning objectives Knowledge: - Understand the definition, causes, current situation of light pollution, and its impact on people, plants and animals Problem-solving skills: - Master the steps and principles of engineering design in the design of a school yard lighting program. Attitudes and values (if needed): - Enhance the ability and awareness of implementing ecological environmental protection.	
Learner analysis Knowledge or problem-solving skill acquired: - The definition, causes, current situation of light pollution, and its impact on people, plants and animals. - Biology: Investigation steps and principles of campus plants. - Physics: Straight line propagation of light, reflection and refraction of light and influencing factors.	
Authentic learning task Design an eco-friendly and practical lighting scheme for the school courtyard.	
Learning content Knowledge: - Biology: Light sensitivity of common plants and animals in the local environment. - Physics: Evaluate the physical parameters of lighting fixtures and environment, such as light intensity, color temperature, etc. - Engineering: The principles and characteristics of engineering design, such as (design is derived from the needs of a specific scenario, design is limited by certain conditions, design is often a trade-off between multiple factors (e.g., functionality, environmental protection)) Problem-solving skills: - Steps and principles of engineering design: define the needs and conditions of school courtyard lighting, conduct field investigation, and produce a plan. Test the plan, revise the plan, and form the final plan.	

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• Geography: Draw a two-dimensional map of the layout of facilities and the distribution of vegetation in the school courtyard. • Mathematics: Data Collection and Analysis. • The use of information and technological tools: a survey of school courtyards using professional laboratory equipment. Use the concept map tool to draw the concept map for the design framework of the courtyard lighting scheme. • Cooperation and communication skills.			
Teaching and learning resources and materials (This may include teaching and learning materials, instruments and materials for inquiry, based on design-based practices, or technological tools. Fill in as needed.) <table border="1"> <tr> <td rowspan="2">Teaching and learning materials</td> <td> • Concept map of light pollution: Self-Constructed by Students • Life habits of common native animals (such as insects and aquatic animals) and plants, especially their sensitivity to light: from Encyclopedia of China • Common Lighting Appliances and Their Physical Parameters • Assessment method of light environment: National standard (GB/T 12454-2017) • Reference cases and ideas of lighting design • Meter ruler: used for field survey and measurement • Camera: used for recording the courtyard environment • Pens and paper: used for drawing two-dimensional map of the courtyard layout • LED lamps with different physical parameters: used to simulate lighting fixtures with different intensities and colors • Illumination detector: used to detect the illumination of the environment </td> </tr> <tr> <td> • iPlant: Identification Software for Native Plants • Animal identification software • Onsp Cloud: Steps and Principles of Engineering Design </td> </tr> </table>	Teaching and learning materials	• Concept map of light pollution: Self-Constructed by Students • Life habits of common native animals (such as insects and aquatic animals) and plants, especially their sensitivity to light: from Encyclopedia of China • Common Lighting Appliances and Their Physical Parameters • Assessment method of light environment: National standard (GB/T 12454-2017) • Reference cases and ideas of lighting design • Meter ruler: used for field survey and measurement • Camera: used for recording the courtyard environment • Pens and paper: used for drawing two-dimensional map of the courtyard layout • LED lamps with different physical parameters: used to simulate lighting fixtures with different intensities and colors • Illumination detector: used to detect the illumination of the environment	• iPlant: Identification Software for Native Plants • Animal identification software • Onsp Cloud: Steps and Principles of Engineering Design
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	• iPlant: Identification Software for Native Plants • Animal identification software • Onsp Cloud: Steps and Principles of Engineering Design		
Instruments and materials for inquiry/design			
Technology, tools, or media			

Teaching & Learning activities		
Phase	Teacher activity	Learner activity
Review knowledge about light pollution		Review knowledge about light pollution with the help of concept maps.
Define the design task	• The design task is to design practical and environmentally friendly school courtyard lighting schemes. • Show examples of courtyard design • Show examples of lighting design • Provide information on the sensitivity of local plants and animals to light	• Discuss and ask questions about the design task • Define the requirements of courtyard lighting design: featuring both practical and environmentally friendly

Page 3

Understand the methods and tools required to complete the design task	- Explain the method of engineering design: define the requirements, investigate the requirements (the purpose is to further refine the requirements), generate the scheme, test the scheme, improve the scheme, form the final scheme and write the report - Explain the methods of field investigation and data analysis: sampling, measuring, recording and summarizing the results. Explain how to draw the distribution plan of animals, plants and facilities in the courtyard. - Introduce how to write a task report, such as describing the product to be designed, specific requirements, design scheme, implementation of the scheme, test of the scheme, improvement of the scheme, final scheme and test results, etc. - Explain how to use the tools: (1) For field investigation: meter ruler, mobile phone APP for plant identification, and animal identification software; (2) usage of led lamp; (3) the scheme of light environment evaluation; and (4) the usage of illuminometer.	Groups discuss and ask questions about methods and tools relevant to the design task.
Field study of investigating needs for design	- Provide feedback on the survey plan - Prompt issues needing attention in field investigation	- The team develops and implements a plan for investigating yard facilities and the distribution of organisms. Different groups are responsible for different survey objects, such as building facilities, shrubs, trees, animals. - Students draw a map of courtyard facilities and animals and plants distribution to further refine the requirements of courtyard lighting design, such as the placement of lamps should avoid light-sensitive plant and animal distribution areas.
Complete the design task	Prompt the issues needing attention in each design link (for example, encourage students to think from multiple perspectives when generating the scheme, such as	Generate scheme: Students choose different types and quantities of led lights to be placed in different positions of the distribution plan of animals and plants in the courtyard.

Page 4

	changing the light source, changing the transmission path of light, protecting photosensitive animals and plants, etc.; pay attention to responding to the design requirements when improving the scheme)	indicating different lighting schemes. • Selection and implementation of schemes: Students discuss and demonstrate different lighting solutions in small groups. • Test schemes: test the scheme effect according to the light environment evaluation method. • Improve schemes: use the light detector to measure the light intensity and color indicators of each lighting position on the map, and adjust the lighting scheme according to the test results in combination with the distribution of animals, plants and functional areas. • Form the final scheme and write the design report.
Report and summary	• Organize students to report the design plan • Comment on, question and summarize the design process and design scheme	• The group reports on the lighting plan and answers questions. • Reflect and revise the design report

Learning assessment		
Evaluation subject	Evaluation tool	Evaluation criteria/dimensions
Teachers, students	Presentation of designed solution	• Practicality • Environmental sustainability • Scientific rigor • Aesthetics • Cost-effectiveness

Fig. 2. An example of STEM curriculum design

2.3.1. Stage 1: Determine the learning objectives and analyze target learners

The topic of the example is “light pollution”. The educational level of the target learners is set to be seventh grade. The learning objectives include the application of multidisciplinary knowledge to understand the light pollution problem (e.g., its definition, causes, current status, and solutions), the development of problem-solving skills, and the formation of appropriate attitudes towards pollution issues.

2.3.2. Stage 2: Design core components of the curriculum

The learning task in this example is to design an eco-friendly lighting scheme for the school courtyard, which can balance the needs for regular human activities at night and the needs to mitigate the harm of artificial light to plants and animals.

The learning content starts with the subject knowledge in biology (e.g., plant and animal species, their needs for and sensitivity to lighting) and physics (e.g., characteristics of light and parameters of lighting). Moreover, it includes the knowledge and skills requested for completing the learning task, such as the engineering design process, conducting investigations of natural living, using technological tools for identifying species, measuring sizes of their distribution areas, and drafting the design. Previously acquired knowledge and skills (e.g., basic light properties, investigation skills) are noted in the learner analysis part. New knowledge and skills required for the task are listed in the learning content part.

Teaching and learning materials for the above-mentioned learning content are prepared. In addition to learning materials for subject knowledge, task-focused learning materials are also included, for example, the document “Assessment methods of light environment” introducing the methods for evaluating lighting schemes, and the instruments and tools (metre rulers, and detectors) for field investigation and lighting scheme design.

Teaching and learning activities include the following. Phase 1: learners are asked to review the knowledge of light pollution. Phase 2: the teacher announces the learning task. Phase 3: the teacher introduces the methods and tools required for the learning task. Phase 4: the pre-task preparation (e.g., a field study for investigating the requirements for the design) is implemented; for example, learners investigate the species, their distribution and sensitivity to lights, and human needs for light. Phase 5: learners work on the task by designing, implementing, testing, and improving the lighting scheme and write up the final scheme in the task report. Phase 6: students present their design outputs to the class and receive feedback from the teacher and peers based on assessment rubrics involving several criteria such as practicality, environmental sustainability, scientific rigour, aesthetics, and cost-effectiveness.

2.3.3. Stage 3: Write up the curriculum plan

Finally, the curriculum design plan is written up in detail after reviewing the entire design to ensure consistencies among different components. Further adjustments can be made based on teaching practices and peer comments if available.

3. Method

A STEM teacher training program was provided to pre-service teachers by using the proposed visible thinking approach to support their learning of integrated STEM curriculum design. The participants' STEM curriculum design outputs and their comments on the visible thinking approach and the training program were collected to examine the feasibility and effects of the proposed approach.

3.1. Participants

Twenty-seven pre-service teachers (24 females, 3 males) from a normal university in south China participated in this study using the visible thinking approach to support their learning of designing integrated STEM curriculum. All participants were majoring in science education and had received little training in STEM education. This study is approved by the Human Research Ethical Committee of the researcher's university, and all participants signed consent forms prior to the study.

3.2. Learning materials

The learning materials included (1) a process model for STEM curriculum design, with key strategies and guidelines for each step, (2) a scaffold for the design of STEM teaching and learning activities, and (3) two examples of STEM curriculum design, each presented in a process and scaffold mentioned above. Both examples were designed on the topic "light pollution", with one focusing on inquiry-based learning (i.e., investigating whether the artificial light pollution affects the growth of chrysanthemums) and the other focusing on design-based learning (i.e., designing an eco-friendly lighting scheme for the school courtyard).

3.3. Procedure

The training program involved five sessions over a period of two weeks. In the first session, participants were introduced to the training program before signing the consent form. A pre-test survey was administered to collect participants' demographic information. After that, participants were given one hour to complete a STEM curriculum design task on the topic of "light pollution".

The second session introduced integrated STEM education and STEM curriculum design and demonstrated the visible thinking approach for integrated STEM curriculum design. Two curriculum design examples on the topic of "light pollution" were used for illustration. At the end of this session, participants made self-reflection on their curriculum design outputs produced on the first day.

In the third and fourth sessions, the participants practised STEM curriculum design on the topic of "Photovoltaics applied in the farm" using the visible thinking approach. The inquiry-based curriculum focused on the learning task "Whether the use of photovoltaics affected the growth of farm plants," whereas the design-based curriculum focused on the learning task "Designing an eco-friendly solar panel layout to address the conflict between solar panels and the light requirements of crops." After the design task, the participants shared and discussed their designed outputs with peers. At the end of the session, feedback from the instructors was provided for participants to improve their curriculum design.

In the last session, participants were given one hour to complete a STEM curriculum design task on the topic “Hydropower and dam construction”. They could choose to focus on either the inquiry-based learning task (investigate the influences of dam construction on the growth of plants upstream of the dam) or the design-based learning task (design an eco-friendly dam construction scheme balancing the needs for power generation and protecting the surrounding natural environment). An open-ended survey was administered to collect participants’ comments on the visible thinking approach.

3.4. Measures and instruments

3.4.1. Curriculum design performance

The curriculum design performance was assessed through pre-test and post-test by asking participants to design a STEM curriculum for a specific authentic topic within 60 minutes. The authentic topics for the pre-test and post-test were “light pollution” and “hydropower and dam construction”, respectively. In both tests, participants first explored the background information of the given authentic topics, and then they chose to design a STEM curriculum that was either inquiry-based or design-based. Participants were allowed to use the process model for STEM curriculum design and the scaffold for the design of STEM teaching and learning activities in the post-test.

Participants’ curriculum designs were evaluated by using the scoring rubrics presented in Table 3. The rubrics were developed based on the literature on curriculum design and STEM education (Goldston et al., 2013; Großmann & Krüger, 2023; Guzey et al., 2016; Jacobs et al., 2008). The rubrics examined nine curriculum design components, including learning objectives, analysis of learners’ prior knowledge and skills, learning task, knowledge-focused learning points, task-focused learning points, knowledge-focused teaching and learning materials, task-focused teaching and learning materials, teaching and learning activities, and learning assessments.

Note that each curriculum design component may involve more than one item. For instance, the component “learning objectives” might include three items that focus on knowledge acquisition, problem-solving skills development, and attitude formation, respectively. Each component is evaluated by considering the performance on each item and the performance across items within the component. The performance on each item is assessed in terms of relevance and appropriateness, among others; the item score is the average of all dimension scores. The across-item performance within a component is assessed in terms of sufficiency and other dimensions; the scores for all dimensions are averaged. Then, the score for each component can be attained by using formula (1). Finally, the score for a curriculum design is the average of the scores for its nine components.

$$\text{Score} = [\text{AVERAGE (all across-item dimensions)} + \text{AVERAGE (all items)}]/2 \quad (1)$$

The first author trained a research assistant to be familiar with the curriculum design evaluation rubrics. After training, they adopted the curriculum design evaluation rubrics to score the pre-test and post-test curriculum design constructed by the pre-service teachers. Cohen’s kappa ranged from 0.84 to 0.99 for all curriculum design components, indicating a strong inter-rater reliability. Any inconsistency was discussed to reach agreement between two raters.

Table 3
Rubrics for assessing STEM curriculum design

Curriculum design component		Assessment Dimension	Scoring
1. Learning objectives	Across items	Sufficiency: The learning objectives such as the acquisition of knowledge and skills are adequately specified.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No learning objectives
	Each item	Appropriateness: The learning objective is aligned with the curriculum standards of the subjects covered in the lesson.	3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate
2. Analysis of learner's prior knowledge and skills	Across items	Sufficiency: The learners' prior knowledge and/or skills relevant to the lesson are adequately identified.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No prior knowledge or skill is identified
	Each item	Relevance: The identified learners' prior knowledge and/or skills are relevant to the lesson. Appropriateness: The identified learners' prior knowledge and/or skills are consistent with their educational level.	3: Mostly relevant 2: Partially relevant 1: Mostly irrelevant 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate
3. Learning task	N.A.	Consistency: The learning task is consistent with the learning objectives of STEM education. Appropriateness: The learning task focuses on investigating or solving real-world problems that are appropriate for the learners in terms of their prior knowledge and/or skills. Feasibility: The task can be implemented with materials and resources accessible to learners. Cross-disciplinarity: The learning task requests the application of knowledge and skills from two or more STEM disciplines	3: Mostly consistent 2: Partially consistent 1: Mostly inconsistent 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate 3: Mostly feasible 2: Partially feasible 1: Mostly unfeasible 3: Covering knowledge and skills from two or more STEM disciplines. 2: Covering knowledge and skills from one STEM discipline and non-STEM disciplines. 1: Covering knowledge and skills from one STEM discipline.
4. Knowledge-focused learning points	Across items	Sufficiency: The subject knowledge that learners are expected to acquire and/or apply in the lesson has been adequately specified.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No subject-matter knowledge is identified
	Each item	Relevance: The subject knowledge that learners are expected to acquire and/or apply in the lesson is relevant to the learning task. Appropriateness: The subject knowledge that learners are expected to acquire and/or apply in the lesson is appropriate for the learners in terms of their prior knowledge and/or skills.	3: Mostly relevant 2: Partially relevant 1: Mostly irrelevant 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate
5. Task-focused learning points	Across items	Sufficiency: The methods and/or tools requested for the learning task are adequately specified.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No method or tool is identified
	Each item	Relevance: The identified method or tool is relevant to the learning task. Appropriateness: The specified methods and/or	3: Mostly relevant 2: Partially relevant 1: Mostly irrelevant 3: Mostly appropriate

		tools requested for the task is appropriate for the learners in terms of their prior knowledge and/or skills.	2: Partially appropriate 1: Mostly inappropriate
6. Knowledge-focused teaching and learning materials	Across items	Sufficiency: The suggested materials and resources are sufficient for the acquisition of requested subject knowledge.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No knowledge-related material is identified
	Each item	Relevance: The suggested material or resource is relevant to the subject knowledge requested in this lesson. Appropriateness: The suggested material or resource is appropriate for the learners in terms of their prior knowledge and/or skills. Reliability: The suggested material or resource is from reliable sources.	3: Mostly relevant 2: Partially relevant 1: Mostly irrelevant 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate 3: Mostly reliable 2: Partially reliable 1: Mostly unreliable
7. Task- focused teaching and learning materials	Across items	Sufficiency: The materials and resources for addressing the learning task are adequately suggested.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No task-focused material is identified
	Each item	Relevance: The suggested material or resource is relevant to the learning task. Appropriateness: The suggested material or resource is appropriate for the learners in terms of their prior knowledge and/or skills. Reliability: The identified material or resource is from reliable sources.	3: Mostly relevant 2: Partially relevant 1: Mostly irrelevant 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate 3: Mostly reliable 2: Partially reliable 1: Mostly unreliable
8. Teaching and learning activities	Across items	Sufficiency: Learning activities are adequately proposed Consistency: The teacher and students' roles in these activities are consistent with learner-centered pedagogy. Organization: The activities are coherent and logically organized.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No teaching and learning activity is listed 3: Mostly consistent 2: Partially consistent 1: Mostly inconsistent 3: Mostly logical and coherent 2: Partially logical and coherent 1: Mostly illogical and incoherent
	Each item	Sufficiency: Necessary details are provided. Appropriateness: The activity is consistent with the learning task.	3: Covering almost all details 2: Missing some details 1: Missing most details 0: No detail is provided 3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate
9. Assessment methods	Across items	Sufficiency: The assessment is sufficient to assess the achievement of the learning objectives.	3: Covering almost all items 2: Missing some items 1: Missing most items 0: No assessment is presented
	Each item	Appropriateness: The assessment is consistent with the learning objectives.	3: Mostly appropriate 2: Partially appropriate 1: Mostly inappropriate

3.4.2. Participants' comments on the visible thinking approach

The participants' comments on the visible thinking approach were collected by asking them to provide written responses to three open-ended questions: (1) What are the

benefits of the proposed visible thinking approach for your learning of integrated STEM curriculum design? (2) What difficulties did you experience when using the proposed visible thinking approach for your learning of integrated STEM curriculum design? (3) What are your suggestions for improving the visible thinking approach and/or the training program?

Participants' responses were qualitatively analysed using thematic analysis, allowing researchers to identify common patterns of meaning (Braun & Clark, 2006). Followed the six steps developed by Braun and Clark (2006), the authors first thoroughly read the responses of participants. Then, primary codes were continuously developed based on key phrases and sentences highlighted in the responses. Through categorizing and combining the codes, several themes were identified. The themes were reviewed and modified by further combining similar themes or adding new themes or sub-themes based on two coders' independent coding. At the end, the final themes were determined and defined for further coding.

The responses were analysed by the first authors, and a blind round examination was conducted by a trained research assistant. The inter-rater reliability reached 0.90, and any inconsistencies in the coding of the responses were discussed until agreement was reached. It is important to note that a single response could encompass multiple aspects, resulting in coding into different themes.

3.5. Data analysis

Cohen's kappa was used to calculate the interrater reliability in scoring the curriculum design and coding of responses to open-ended questions. The paired-samples *t*-test was employed to investigate the differences between participants' pre-test and post-test curriculum design performance. Besides *p*-value, the effect size measure, i.e., Hedges' *g*, was calculated to indicate the strength of the intervention effect for the study of small sample size (Hedges, 1981). Thematic analysis was employed to find common themes among participants' responses to the open-ended survey.

4. Results

4.1. Curriculum design performance

Paired-samples *t*-tests were performed to compare changes in participants' STEM curriculum design performance from pre-test to post-test. The descriptive statistics and paired-samples *t*-test results are presented in Table 4. Participants showed statistically significant improvements in all curriculum design components, except learning objectives, analysis of learners' prior knowledge and skills, and task-focused teaching and learning materials. Based on the effect size (Hedges' *g*), large effects were detected for designing teaching and learning activities ($g = 1.565$) and total curriculum design scores ($g = 1.156$), whereas moderate effects were detected for task-focused learning points, knowledge-focused teaching and learning materials, and assessment methods. These results suggested that the teacher training program featuring the proposed visible thinking approach enhanced participants' STEM curriculum design performance, especially for designing teaching and learning activities, which was the most intricate curriculum design component among others.

Table 4

Paired-samples t-test for the pre-test and post-test curriculum design

Curriculum design component	<i>N</i>	Pre-test		Post-test		<i>df</i>	<i>t</i>	Sig.	Effect sizes (Hedges'g)
		Mean	<i>SD</i>	Mean	<i>SD</i>				
1. Learning objectives	27	2.599	0.354	2.704	0.399	26	1.105	0.140	0.206
2. Analysis of learner's prior knowledge and skills		2.228	0.622	2.344	0.377		0.913	0.185	0.171
3. Learning task		2.231	0.901	2.676	0.409		2.153*	0.020	0.402
4. Knowledge-focused learning points		1.916	0.331	2.160	0.394		2.307*	0.015	0.431
5. Task-focused learning points		2.012	0.626	2.517	0.550		2.966**	0.003	0.554
6. Knowledge-focused teaching and learning materials		1.952	0.685	2.476	0.380		3.750***	0.000	0.701
7. Task-focused teaching and learning materials		2.544	0.366	2.620	0.329		0.826	0.208	0.154
8. Teaching and learning activities		2.052	0.357	2.677	0.233		8.379***	0.000	1.565
9. Assessment methods		2.284	0.655	2.707	0.417		2.899**	0.004	0.542
Total		2.202	0.247	2.542	0.177		6.190***	0.000	1.156

Note. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

4.2. Participants' comments on the visible thinking approach

Participants' comments on the visible thinking approach were collected by the open-ended survey and were analyzed through thematic analysis. Their comments on the benefits of the visible thinking approach are outlined in Table 5. Most participants mentioned that the proposed approach offered clear guidance and a systematic framework for STEM curriculum design. They also claimed that the approach supported their analysis and reflection on the designed STEM curriculum and scaffolded their design of STEM curriculum design. Moreover, they indicated that the visible thinking approach facilitated their comprehension of STEM education, and enhanced their self-efficacy and motivation to design STEM curriculum.

Participants' comments on the difficulties in using the visible thinking approach and suggestions for improvement are outlined in Table 6. Participants mentioned that they need more time to digest the training materials. In addition, they found it challenging to integrate knowledge across multiple disciplines and it was difficult to find sufficient resources and materials to support the designed learning task. Participants also felt uncertain about the implementation of the designed STEM curriculum. To benefit more from the training program, participants suggested more time provided for training. Moreover, participants expressed their hope to obtain more STEM curriculum design examples and more STEM teaching and learning materials or resources.

Table 5

Benefits of using the visible thinking approach for integrated STEM curriculum design

Theme	Illustrative Example	Frequency
1. Provide clear guidance for STEM curriculum design	<i>The scaffolding materials provide a clear guidance for designing the curriculum.</i>	19
2. Offer a systematic framework for STEM curriculum design	<i>The scaffolding materials provide a systematic and comprehensive framework for developing the curriculum.</i>	10
3. Support analysis and reflection on designed STEM curricula	<i>I could better reflect my curriculum design based on the supporting materials. The process model and the scaffold supported me to analyse the provided curriculum design examples to inform my design.</i>	8
4. Enhance the understanding of integrated STEM education and curriculum	<i>I understand better about integrating multiple disciplines in the STEM curriculum.</i>	7
5. Scaffold the process of STEM curriculum design	<i>When I determined the learning content, I found multi-disciplinary knowledge centred on the learning task.</i>	6
6. Increase self-efficiency in STEM curriculum design	<i>As a novice, I was more capable of designing STEM curriculum.</i>	6
7. Achieve the potential of STEM education	<i>The STEM curriculum designed based on this approach could cultivate students' competencies.</i>	4
8. Improve my motivation to design high-quality STEM curricula	<i>I hope I could use this approach to design more high-quality STEM curricula in the future.</i>	1

Table 6

Difficulties in using the visible thinking approach to design integrated STEM curriculum and suggestions for improving the visible thinking approach or the training program

Theme	Illustrative Example	Frequency
<i>Difficulties</i>		
1. Need more time to digest the training materials	<i>Due to time constraints, I often end up adopting the first relevant reference and materials that I find. This leaves me feeling insecure during the design process. I would request more time for selecting teaching materials and technological tools.</i>	15
2. Difficulty in integrating knowledge across multiple disciplines	<i>It's hard to identify learning content regarding the dam construction from multiple disciplines.</i>	6
3. Not sure of the implementation of the design STEM curriculum	<i>I am hesitating about whether I should ask students to conduct investigations on the dams in site or online.</i>	5
4. Lack of STEM teaching and learning materials	<i>I don't know how to find learning materials to support the designed learning task.</i>	4
<i>Suggestions</i>		
1. More time is needed for such kind of training	<i>It would be better to provide more time for us to reflect on and improve our own curriculum design.</i>	13
2. Provide more example of STEM curriculum design	<i>I would like to see more examples of design-based learning activities to better understand its process and rationales.</i>	7
3. Recommend more STEM teaching and learning materials or resources	<i>It would be better for the tutor to recommend some reliable resources for us to search for course materials.</i>	2

5. Conclusion and discussion

To promote integrated STEM education, it's important to design high-quality STEM curricula. However, STEM curriculum design is a complex task involving multiple components and complicated processes to coordinate the components into a coherent design. Existing STEM teacher training programs fail to provide sufficient guidance on how to deal with the complexity in STEM curriculum design.

To address the gap, this study proposed a conceptual framework that visualizes the complex process of STEM curriculum design. The conceptual framework includes (a) a process model for STEM curriculum design, with key strategies and guidelines for each step, and (b) a scaffold for designing STEM teaching and learning activities.

This study also explored the use of the visible thinking approach to a STEM teacher training program. The participants made a significant improvement in their STEM curriculum design performance from pre-test to post-test, especially in the design of teaching and learning activities. Participants' comments highlight the benefits of the proposed approach, in particular its provision of a systematic framework and clear guidelines for STEM curriculum design. The study demonstrates the feasibility and promising potential of the visible thinking approach in supporting teacher learning of integrated STEM curriculum design.

Author Statement

The authors declare that there is no conflict of interest.

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