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Article

A design of integrated STEM constructive games in developing the Four Cs in early elementary students

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Abstract

The science, technology, engineering, and mathematics (STEM) approach has proven reliable in developing critical thinking, collaboration, communication, and creativity skills (the Four Cs). However, research on implementing the STEM approach in the context of early elementary school student development remains limited. To address this gap, this research integrates the STEM approach with constructive play, referred to as the iSTEM-C Game. The game was developed using the mechanics, dynamics, and aesthetics (MDA) framework. This study aims to explore two questions: How do students perform on the Four Cs during the implementation of the iSTEM-C Game, and why is the iSTEM-C Game effective in boosting Four Cs performance? The research employed a qualitative case study approach, involving 98 students from four elementary schools in Sleman Regency, Yogyakarta. Participants were selected through purposive sampling based on saturation mechanisms. Data collection was conducted using video recordings, field notes, and a 30-item structured observation sheet. The pattern matching technique was used to compare empirical findings with expected patterns during data analysis. The research findings indicate that the iSTEM-C game mechanism is key to promoting Four Cs performance through three critical elements: diverse tools presented before discussion, rules integrated with real-world problems, and cognitively tailored challenges. The novelty of this research lies in a practical pedagogical framework that facilitates game-integrated STEM implementation, tailored to the concrete operational cognitive stage, to promote the development of the Four Cs through three game stages: planning, try and retry, and show-play.

1. INTRODUCTION

Elementary education is universally recognised as the foundation for strong educational systems [1]. Beyond equipping students with fundamental knowledge, this educational stage holds significant potential for cultivating 21st-century skills crucial for students' future success. These skills include critical thinking and problem-solving, creativity, collaboration, and communication, collectively known as the Four Cs.

The Four Cs framework is based on the internationally recognised Partnership for 21st Century Learning [2]. This framework categorises these skills into four main dimensions: creativity and innovation, critical thinking and problem-solving, communication skills, and collaboration skills. Each dimension has specific operational definitions. Critical thinking and problem-solving skills refer to students' ability to process information and make evidence-based decisions. Collaboration is defined as the ability to work together and share responsibilities with others. Communication encompasses the ability to convey and receive information effectively. Creativity refers to the capacity to generate innovative ideas and solutions. These four skills are interconnected and systematically influence one another.

Exploratory factor analysis conducted with early elementary students reveals that communication skills significantly relate to critical thinking and problem-solving abilities. This relationship is particularly strong in collaborative contexts, indicating that students' capacity to analyse information, evaluate arguments, and formulate ideas in discussions is greatly enhanced by effective communication skills that support problem-solving processes [3].

Creativity skills in early elementary students are reflected in their ability to express and create new ideas, demonstrated through enthusiasm for challenges, high curiosity, courage to modify, and willingness to argue in creative contexts [3]. These exploratory factor analysis results align with Ershadi and Winner's assertion that creativity at this age tends to be intrapersonal, personal, and contextual, focusing on openness to new experiences and exploration of the unknown [4].

Developing these skills from an early age is critically important. Students at this developmental phase are highly responsive to various environmental stimuli and have begun processing information through concrete direct experiences, supported by more organised thinking patterns and developing inductive logic. The developmental progression from egocentrism to sociocentrism enables students to begin understanding and accepting others' perspectives, a crucial requirement for effective collaboration and communication [5].

The STEM (Science, Technology, Engineering, and Mathematics) approach has been empirically proven effective in supporting Four Cs development. The main strength of STEM lies in its ability to enhance learning experience quality through engagement in authentic situations [6], providing comprehensive and integrated learning experiences [7].

Researchers have conducted various STEM implementations in elementary education contexts, though most target upper elementary students. Previous research applied STEM to fourth-grade students through five core engineering design processes: problem scoping, idea development, design and construction, design evaluation, and redesign. The learning material was based on aerospace engineering problems, focusing on aircraft model design and redesign tasks. Findings showed that the practical application of science and mathematics concepts occurred primarily during the evaluation and redesign phases [8]. However, this approach emphasised abstract representations such as technical sketches and mathematical calculations, which are less suitable for students at the concrete operational stage, who need direct physical object manipulation to understand concepts.

Another STEM implementation involved fifth-grade students in bridge construction projects, conducted in stages from simple cardboard bridges to arduino-controlled bridges with traffic light programming [9]. While this project provided positive impacts across cognitive, affective, and psychomotor domains, the increasing complexity in the final stages demanded abstract thinking abilities that have not yet developed optimally in early elementary students.

This raises an important question about how STEM implementation should be adapted to best suit early elementary students' characteristics. In principle, providing quality STEM experiences from an early age is important [10], with no age limit, too early to begin STEM implementation [11]. This emphasises that STEM learning strategies must be integrated with approaches relevant to students' developmental characteristics.

An inherent characteristic of early elementary students is their natural inclination towards play. Froebel stated that play is not merely recreational but rather the primary way children learn [12]. Play enables idea exploration, creativity development, and the natural emergence of complex skills [13]. As the main driver of children's emotional, physical, language, and cognitive development [14]. Integrating STEM with play activities represents a promising strategy for developing the Four Cs.

Current STEM and game integration often utilises computer-based or mobile device digital platforms. Several research results on digital platform utilisation in STEM implementation show effectiveness in improving learning outcomes in certain domains [15]. However, digital game-based STEM approaches have not fully met the criteria for ideal educational games, which must contain elements of meaningfulness, active engagement, enjoyment, repetition, and meaningful social interaction [16]. In the context of supporting the Four Cs development in early elementary students, these elements are crucial to fulfill according to students' developmental characteristics.

Piaget's theory classifies games based on developmental stages: sensorimotor play, symbolic play, and games with rules. Early elementary students are at the concrete operational development stage, where games with rules become more dominant [17]. Students have understood concrete rules and often create their own rules while playing. As they mature, students become increasingly capable of understanding simple to more complex rules.

One type of game with rules is constructive play, a game performed to create something. Constructive play is usually done using LEGO or blocks, where each set typically consists of various shapes and sizes that can be explored or manipulated to create something [18], [19]. Thus, the characteristics of constructive play align perfectly with the STEM approach.

The explorative and manipulative nature plays a role in the process of discovering knowledge in problem-solving (science). The variety of tools in constructive play mirrors the variety of technologies used to solve problems (technology). The design process using various technologies to solve problems, represents engineering. Measuring tools or measurements in technology and engineering applications connect to mathematics [20]. Through these alignments, STEM-integrated constructive play (iSTEM-C Game) has the potential as a new approach in implementing STEM according to students' characteristics at the concrete operational stage.

To design an effective iSTEM-C Game approach, used the Mechanics-Dynamics-Aesthetics (MDA) framework. This framework ensures that the game structure is designed systematically, dynamically, and attractively, creating educational play experiences [21],[22]. Mechanics are the game systems. Dynamics are the interaction patterns created based on the game systems. Aesthetics are the impacts of mechanical and dynamic interactions, namely the development of critical thinking and problem-solving skills, collaboration skills, communication skills, and creativity skills.

This research provides original contributions in three main aspects: (1) filling the gap in STEM implementation studies for early elementary students that remain minimally explored, (2) combining the STEM approach with constructive play suitable for concrete operational stage characteristics, and (3) presenting a systematic theoretical structure through the MDA framework to effectively support the Four Cs development.

With this theoretical foundation and conceptual framework, this research aims to explore the design of the iSTEM-C Game and identify how this game can promote the Four Cs skills development in early elementary students. Two research questions are proposed:

1. How is the performance of students' Four Cs during the implementation design of the iSTEM-C Game?
2. Why is the design of the iSTEM-C Game effective in promoting the development of the Four Cs?

This research uses a qualitative case study approach with pattern-matching analysis techniques to connect theoretical patterns with empirical data. This study contributes to the development of a new pedagogical design for STEM integrated with constructive play according to concrete operational development characteristics in developing the Four Cs of early elementary students.

2. CONCEPTUAL FRAMEWORK

2.1 Theoretical foundation of the iSTEM-C Game

Problem-based STEM learning (STEM-PBL) stands as one of the most widely adopted approaches in STEM education and has been recognised as an established method at the elementary school level [23]. Through this approach, students encounter complex, authentic, and unstructured problems, typically presented as open-ended questions that are explorative in nature, such as "why" and "how" [24]. These open-ended questions are deliberately designed to stimulate students' critical thinking and analytical abilities when facing real-world challenges.

Recent studies demonstrate that the STEM-PBL approach enhances academic achievement while strengthening mastery of the Four Cs, competencies essential for addressing future challenges [25]. Five main pillars underpin effective STEM-PBL implementation: problems should be open, complex, and contextual; group work should promote social interaction and idea exchange; technology and STEM tools should be used in an integrated manner; scientific inquiry should be applied systematically; and students should reflect on and present evidence-based solutions [23].

However, complex problems that are unstructured and abstract can potentially create excessive cognitive load for early elementary students who have not yet fully mastered the hypothetical-deductive reasoning necessary to solve such problems [26]. Their logical thinking ability remains limited to concrete objects and directly observable situations [5].

This cognitive limitation represents a natural developmental stage that must be respected rather than viewed as a weakness. Jean Piaget emphasised the importance of active involvement in knowledge construction [26]. This construction occurs through three key processes: assimilation, accommodation, and equilibrium.

Assimilation happens when new information can be integrated into existing cognitive schemas; accommodation occurs when existing schemas need modification to accommodate new information; and equilibrium is achieved when individuals successfully align new knowledge with their existing cognitive structures [26],[5]. This entire process depends heavily on concrete experiences and inductive logic, the ability to draw conclusions based on observation of specific phenomena [27].

Complementing Piaget's perspective, John Dewey argued that effective educational experiences begin when students encounter confusing situations that subsequently motivate them to take action [28]. Such problematic situations must be capable of arousing curiosity and stimulating exploration, yet remain carefully designed to avoid creating excessive emotional or cognitive burden.

Therefore, the iSTEM-C Game design incorporates problems that are real, contextual, and closely connected to students' lives. This approach encourages direct exploration and active problem-based learning, with a strong emphasis on concrete experiences. This enables students to construct new knowledge meaningfully according to their cognitive development stage while simultaneously promoting the strengthening of critical thinking, communication, collaboration, and creativity skills in an integrated manner.

2.2 Concept of STEM integrated constructive game (iSTEM-C Game)

Constructive play represents a form of play that emphasises utilising various types of materials to create or build something [19], [29]. This approach is deeply rooted in Piaget's cognitive development theory, which emphasises the importance of children's active involvement in the knowledge construction process through exploration and discovery of alternatives in problem-solving. The implementation of constructive play has been introduced since preschool age, beginning with simple object manipulation and gradually developing into more complex activities as students' age and cognitive capacity increase. This play is rich in manipulative activities such as arranging, combining, dismantling, and assembling objects into meaningful forms.

Research on symbolic construction play using geometric pieces similar to puzzles demonstrates its effectiveness. The game materials are arranged in four sets based on specific criteria: the size of the objects is large enough to be easily manipulated, the number of objects is not excessive to avoid limiting exploration, and there is systematic variation in shape, colour, and size.

Each student was given two sets of materials in succession and asked to "make something" freely without instructions or intervention from the teacher. Most students showed initiative in designing construction goals, either through initial planning or by explaining the final results. The activity concluded with a presentation session where students showcased their work [30].

During construction activities, students actively formed visual representations reflecting the real world, including pictures, buildings, cities, or landscapes. Throughout the construction process, they developed themes and explored new possibilities while arranging objects with increasing complexity and structure. This reflects the significant role of constructive play in encouraging creativity, imagination, and the gradual development of symbolic thinking.

Another implementation uses unity blocks, hardwood blocks measuring 3.5 × 7 × 7 cm. These blocks include variations in shapes such as half units, curves, triangles, and cylinders. To enrich the context, miniature accessories of humans, animals, vehicles, and traffic signs with proportional scale are provided. Students are given full freedom to build and play without direct intervention from teachers or research assistants [31].

Similarly, Sue McCleaf Nespeca developed a STEM education programme that integrates constructive play with various materials. These include blocks, bricks resembling Lego and Duplo, Tinkertoys, Lincoln Logs, and even Play-Doh [19]. In this context, constructive play is defined as an activity of building or creating. It involves assembling small objects into larger structures and producing tangible works after play.

Based on the three implementations of constructive play described, five main characteristics of constructive play can be concluded: (1) the provision of diverse play materials; (2) open instructions and ample space for expression without direct teacher intervention; (3) the absence of a product model to be imitated; (4) an emphasis on exploration, manipulation, and reflection during the play process; and (5) the presentation of works as a form of verbal expression.

These features are consistent with the STEM approach, which promotes problem-solving and autonomous conceptual growth. The provision of diverse play materials or tools to the technology used for problem-solving [32] ample space for expression, and the absence of models to imitate aids students' engineering abilities in using technology with mathematical measurements or estimations. Furthermore, exploration, modification, and reflection are essential for identifying verifiable problem-solving notions [7]. In this demonstration, students may display the quality of their performance in front of their peers and professors.

Based on the features of constructive play and the nature of the STEM approach, a game idea is developed and separated into three stages, as shown in Figure 1. This three-stage framework provides a structured yet flexible approach that allows students to engage with STEM concepts through iterative problem-solving whilst maintaining the playful, exploratory nature essential to a constructive game.

The planning stage focuses on developing students' comprehension of the game's objectives, the rules that must be followed, and the obstacles that must be conquered through collaboration. Students are asked to consider ways to solve the problem without violating the specified guidelines. The try and retry stage, which is focused on exploration and modification, entails doing reflection and assessment until the task is completed. The students' accomplishments are displayed at the show-play stage, where students describe their team's achievement in solving challenges, as well as how the problem-solving principles were discovered.

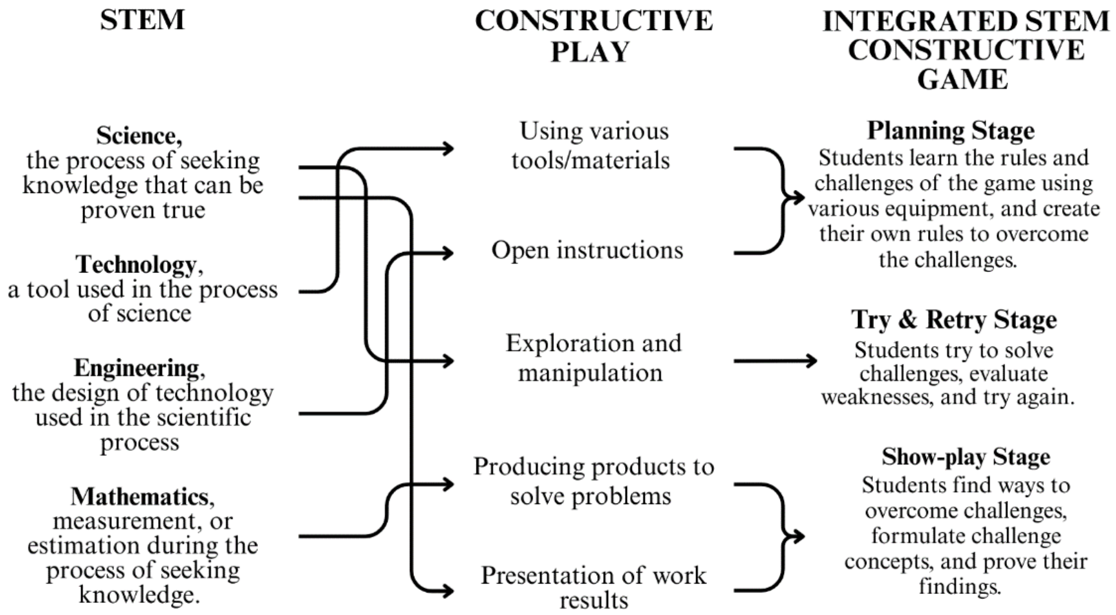


Figure 1. Concept of integrated STEM constructive play.

2.3 Design and implementation of iSTEM-C Game

Formulating the definition of a game constitutes an essential step in game design, as this definition serves as the conceptual foundation that determines the direction and structure of the design to be developed. An ideal game possesses several integrally interconnected characteristics: it is conducted voluntarily to ensure intrinsic motivation; it has clear objectives as guidance; it contains conflict to create challenges; it is governed by rules that form the game structure; it includes a win-lose system as an achievement indicator; it is interactive to facilitate active involvement; it offers proportional challenges to player abilities; it can create intrinsic value that provides satisfaction; it actively engages players in all aspects; and it has a closed and formal system that maintains internal consistency [33].

The problem-solving element constitutes the core of a game, providing intrinsic satisfaction when players successfully complete challenges [33]. Without problematic content, a game loses its essence and becomes merely an ordinary activity [21], [33]. This perspective aligns with Jean Piaget's theoretical framework, which positions problem-solving as a cognitive process that develops simultaneously and progressively [26].

To fulfill these characteristics and ensure integration of problem-solving elements, the iSTEM-C Game design is developed based on the MDA (Mechanics, Dynamics, Aesthetics) framework. These three components interact with each other to create a problematic, interactive, and engaging learning experience, aligned with the essence of games oriented toward developing thinking skills and problem-solving abilities [21], [33].

Mechanics encompass the systems, rules, and interaction structures that enable the game to proceed in an orderly manner, controlling player actions through rules about tool selection, moving water without stepping challenges, and consequences of violations [33]. For mechanics to function effectively, they require technological and narrative support that makes the gaming experience logical, immersive, and meaningful. Technology encompasses not only digital devices but also tools, media, and materials that support exploration and creative interaction.

Dynamics reflect how players respond to challenges, interact with each other, and how the game evolves. In team games, dynamics encourage collaboration that enriches the gaming experience, creating dramatic tension through conflict, emotional release, and satisfying resolution [33].

Aesthetics in the gaming context refers to the emotional and cognitive experiences felt by players, including sensations of challenge, narrative, expression, and meaningful emotional involvement [33]. In educational games, aesthetics integrated learning strategies, academic content, and game elements to achieve cognitive, affective, and psychomotor competencies [34]. But this research, aesthetics focuses on developing the Four Cs skills: critical thinking, creativity, collaboration, and communication, which emerge gradually during the play process.

The iSTEM-C Game design aligns with the learning outcomes of second-grade elementary school students, particularly in natural sciences and mathematics subjects. In science, the targeted competency is "Explaining simple cause-and-effect patterns using media or supporting tools. The mathematics competency is "understanding the concept of non-standard measurement units". Based on these standards, the material incorporated in the game includes properties of liquid substances and length measurement using non-standard measuring tools.

Table 1 outlines the distribution of iSTEM-C Game content within the STEM framework, demonstrating science, technology, engineering, and mathematics components are interconnected within the constructive play context.

Table 1. Distribution of iSTEM-C Game design materials

	Materials	**STEM-integrated Constructive Play**
Science	Properties of liquids	Finding out the properties of liquids through exploration and manipulation
Technology	Water flow tools	Using bamboo, pipes, hoses, sponges, cloths, various containers, and various adhesive tools in the process of discovery.
Engineering	Design for moving water	Designing a way to move water with a relay technique by manipulating water flow tools.
Mathematics	Non-standard measuring instrument	Measuring the distance between the water source and the containers to be filled; estimating the length of the tool needed to channel the water; adjusting the height of the tool so that the water can flow to meet the game rules, where students must move the water without stepping.

Based on this comprehensive conceptual framework analysis, two specific prediction patterns are formulated to answer the research questions:

1. Equipment variety and regulation compliance: The variety of equipment used in compliance with regulations and challenges will support the implementation of game dynamics that

encourage interaction between students and promote the development of critical thinking and problem-solving skills, collaboration skills, communication skills, and creativity skills.

2. MDA framework synergy: The iSTEM-C Game design, structured with the MDA framework, illustrates mechanisms that synergise with game dynamics in creating aesthetics manifested as critical thinking and problem-solving skills, collaboration skills, communication skills, and creativity skills.

These predictions provide testable hypotheses that connect the theoretical framework to empirical implementation, enabling systematic evaluation of the iSTEM-C Game's effectiveness in promoting Four Cs development among early elementary students through STEM-integrated constructive play.

3. Methods and Material

3.1 Research design

This study employs a qualitative approach with a comprehensive exploratory case study method on phenomena in real contexts [35]. The focus of the research includes identifying the performance of the Four Cs in the implementation of the game and exploring the design mechanisms that promote the development of these skills.

3.2 Participants

The participants in this study consisted of second-grade students from four elementary schools located in different districts in Sleman Regency, Yogyakarta Province, Indonesia. Participants were selected using purposive sampling techniques [36]. The selection considered certain characteristics, including teacher enthusiasm and school principal approval. The selection process began by distributing a questionnaire about the teachers' commitment to STEM through district-level cluster leaders. Teachers expressing a high willingness to become STEM practitioners were further selected based on school location. Their willingness to collaborate was confirmed through direct phone communication.

The number of participants was determined based on the principle of saturation [36], meaning that participant selection was stopped when the mechanics of the iSTEM-C Game design were aligned with the dynamics of consistently driving the performance of the Four Cs.

The number of participants involved in this study is displayed in Table 2. Participants of the iSTEM-C Game test.

Table 2. Participants of the iSTEM-C Game test.

Schools	Males	Females	Total
A	11 students	13 students	24 students
B	16 students	12students	28 students
C	11students	10 students	21 students
D	12 students	13 students	25 students
Total			98 students

The involvement of participants has obtained written approval from the principal. Previously, the researchers held a meeting with the principal to explain the concept, objectives, and benefits of the iSTEM-C Game. The researcher emphasised that the implementation would be conducted in one meeting to test the suitability of the game's mechanics, dynamics, and aesthetics against the Four Cs performance and the cognitive development characteristics of the students. Based on the researcher's explanation, the principal welcomed the researcher's request and approved the implementation of the study by directly involving the class teachers.

3.3 Procedure

The researchers designed the iSTEM-C Game in accordance with the applicable national curriculum. The content is focused on the same concepts for all schools. During the implementation process of the iSTEM-C Game design, the researchers involved classroom teachers and research assistants who are final-year students in the elementary school teacher education programme. Initially, the teachers had expressed their willingness to be the implementers.

However, after the teachers studied the iSTEM-C Game design, they proposed a change in roles, considering (1) researchers are considered to have a better understanding of the design, so the implementation can run optimally, (2) teachers do not yet feel ready to implement it independently, and (3) teachers want to observe a direct example of the implementation practice before taking over in the future.

Thus, the researchers were directly involved as the implementers of the iSTEM-C Game design, the teachers were involved as videographers, and the research assistants were involved as observers. Previously, the research assistants had received training and simulation in observing the performance of the Four Cs and recording students' responses to the mechanics of the game. By involving teachers and research assistants in data collection, the internal validity of the research is strengthened.

The implementation mechanism is adjusted based on the evaluation of each trial in the previous school. The mechanism at school A is carried out with the following steps:

1. Planning stage, the students were invited to participate in the Moving Water Game, where they were challenged to move water from one point to another four meters away using a relay technique without stepping. The students are divided into small groups consisting of 4-6 people. Each group receives a game instruction sheet containing a list of equipment, rules, and challenges that must be completed. Next, they are given trigger questions related to the properties of water (students are entitled to answer according to their individual knowledge and personal experience). Various supporting tools were provided for this activity, except for a water dipper, which was intentionally excluded to encourage students' creativity in using alternative tools such as hands, towels, or sponges. The students were then asked to independently discuss their choice of tools, design strategies, and role distribution within their teams.
2. Try and retry stage, the students explored its use according to the agreed-upon strategy. They reflect on the success or failure of the tools they designed.
3. Show-play stage, the students present their design results while demonstrating their understanding of the properties of water. Students who completed the challenge received star stickers as a form of reward. Meanwhile, the unsuccessful group gets the chance to either redesign or terminate the game.

3.4 Data collection

Data collection was conducted through three main techniques: (1) documentation in the form of video recordings; (2) observation sheets containing 30 performance items of the Four Cs, organised based on the results of exploratory factor analysis from previous research, and to facilitate observation, each student was assigned a code number worn on their clothing; and (3) field notes recording related to the performance of the Four Cs as well as students' responses to the game's rules and challenges.

Video recordings and field notes were used to test prediction patterns, while observation sheets served as a comparison in pattern-matching analysis [35]. Notes related to students' responses to the game's mechanics were used to evaluate the design of the iSTEM-C Game. To maximise observation, the 30 performance items of the Four Cs were divided according to the three implementation stages: planning stage, try and retry stage, and show-play stage.

Table 3 demonstrates how the Four Cs are systematically assessed across three implementation stages of the iSTEM-C Game. Critical thinking evolves from listening and interpreting during the planning stage to explaining and reflecting in the try and retry stage, culminating in validating and drawing conclusions at the show-play stage. Collaboration transitions from self-control and compromise to active participation, ultimately manifesting as responsible behaviour. Communication advances from clear articulation to listening to diverse perspectives, reaching fluency in the final stage. Creativity develops from expressing ideas enthusiastically to generating original concepts and exploring the unknown.

This structured progression reveals how game mechanics scaffold students' development of twenty-first century skills through increasingly complex cognitive and social demands.

Table 3. Observation items for the performance of the Four Cs

The Four Cs Component	**Stage of iSTEM-C Game Design**		
	Planning Stage	**Try and retry Stage**	**Show-play Stage**
Critical Thinking and Problem-Solving Skills (10 items)	• Listening to others' opinions until completion • Interpreting problem solutions • Arguing	• Explaining problems • Reflecting • Assessing/evaluating • Connecting problems with experience	• Validating • Drawing conclusions • Conveying information based on data
Collaboration Skills (5 items)	• Self-control/compromise	• Participating • Reminding about agreements/reprimanding Complying with agreements	• Being responsible
Communication Skills (7 items)	• Speaking with clear articulation • Responding/expressing agreement or disagreement Responding to friends' opinions	• Listening to others' perspectives • Expressing opinions according to context Asking questions according to context	• Speaking fluently
Creativity Skills (8 items)	• Expressing ideas clearly • Being enthusiastic about challenges • Being responsive to diverse thinking	• Generating original ideas • Being brave to explore the unknown • Developing/modifying ideas.	• Being fluent in implementing ideas • Being enthusiastic about results

3.5 Data analysis

Data analysis employs a pattern-matching tool to compare anticipated patterns with empirical patterns. Predicted patterns are derived from theoretical research, and actual patterns are acquired through data analysis of video recordings and field notes. Subsequently, it is reevaluated against the observational data. If the actual pattern aligns with the expected pattern, it enhances the validity [35].

This approach was chosen to address two explanatory research questions: "How do the Four Cs function during the implementation of the iSTEM-C Game?" and "Why does the design of the iSTEM-C Game improve the performance of the Four Cs?" Figure 2 illustrates the systematic logic underpinning this pattern-matching approach. It demonstrates how the comparison between theoretical predictions and empirical observations provides robust evidence for causal relationships between game design and Four Cs development.

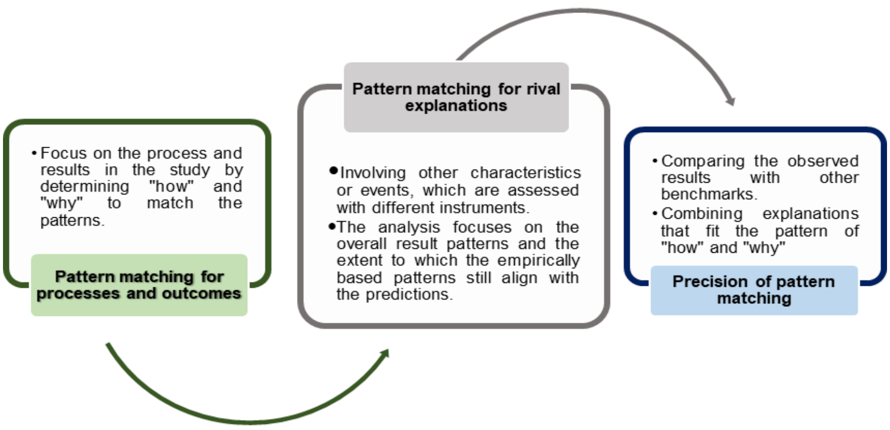


Figure 2. Pattern matching technique illustrates the logical correlation between processes and outcomes.

Figure 3 provides a comprehensive overview of the entire research process. It illustrates how the pattern-matching analysis integrates within a broader methodological framework that spans from initial preparation through to sustainable implementation. This visualisation demonstrates the iterative and interconnected nature of the research stages. Each phase builds upon previous findings to ensure both methodological rigour and practical applicability of the iSTEM-C Game design.

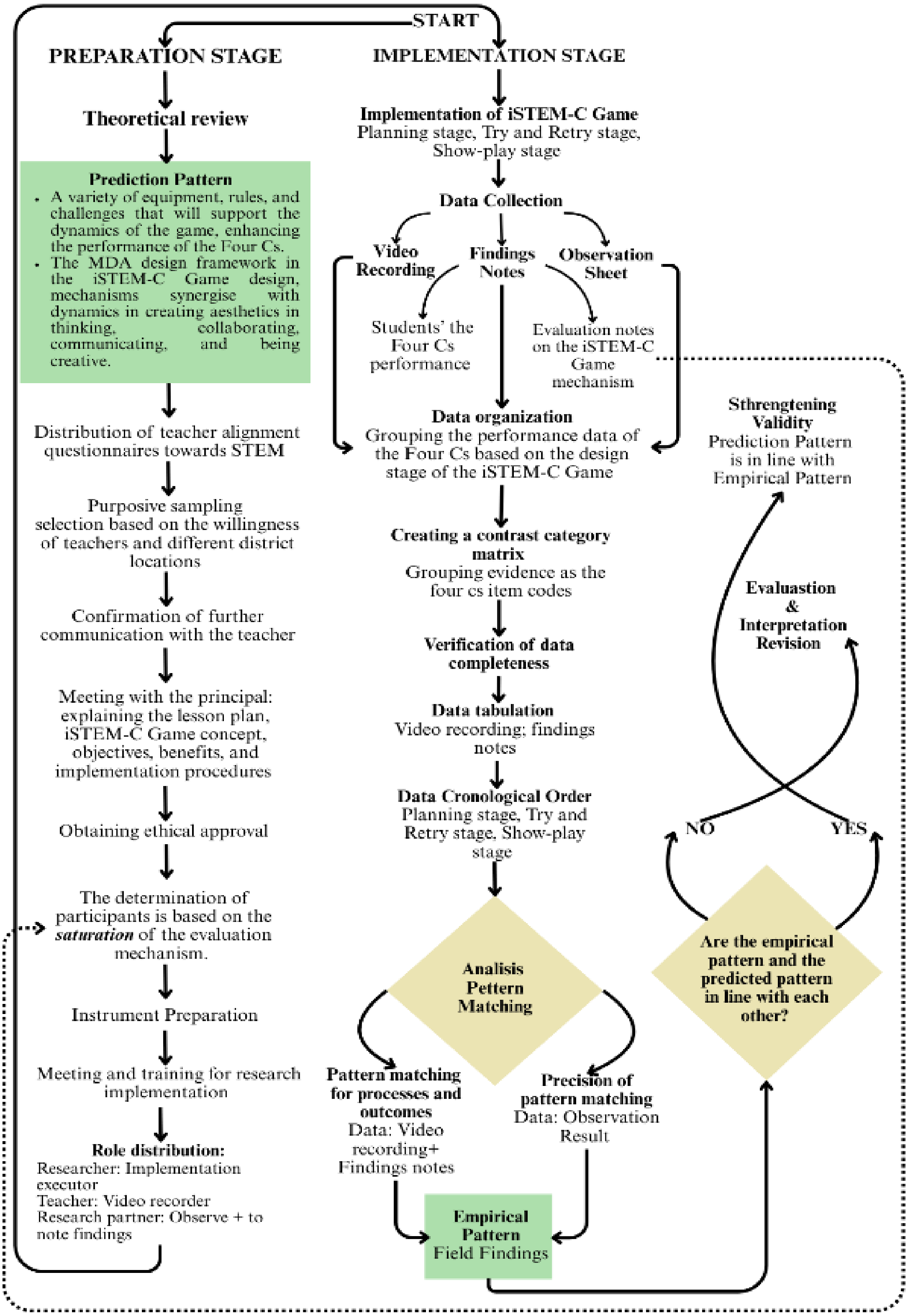


Figure 3. The research flowchart; a visualisation of the research stages from preparation to sustainable implementation.

The analysis steps refer to Miles & Huberman, namely: 1) placing information in a different arrangement by grouping the Four Cs performance data based on the game design stages; 2) creating a contrast category matrix and placing evidence in the form of the Four Cs performance item codes; 3) examining the data; 4) tabulating data from video recordings, finding notes, and observation sheets; and 5) placing information in chronological order of the iSTEM-C Game design stages [35]. For observational data, percentage analysis is used with the formula:

$$P = \frac{\text{Number of observed occurrences aech item}}{\text{Number of students}} \times 100$$

The research findings are reported using the Goal-Question-Metric (GQM) technique, as a systematic and structured framework that connects the research or evaluation objectives with the collected data [37].This structured approach ensures alignment between what the research intends to discover and how the data is collected and analysed.

4. Results

4.1 How did the Four Cs of the students perform during the implementation of the iSTEM-C Game design?

The answer to the first research question will be answered based on the stages of iSTEM-C Game implementation.

4.1.1 The students' performance of the Four Cs at the planning stage

The performance of the Four Cs of the students during the planning stage shows the forms of the Four Cs that emerged when the students were asked to discuss.

Table 4. Students' Four Cs Performance at the planning stage

Goal 1	Evaluate the Four Cs performance (critical thinking, collaboration, communication, and creativity) during the planning stage.
Question 1	How are critical thinking skills demonstrated during the planning stage?
Metrics of critical thinking skills	**1. Arguing** Debates naturally emerged when students determined the water-moving tools and their usage. This spontaneous argumentation demonstrates how the iSTEM-C Game design facilitates authentic critical thinking through problem-based scenarios. Student A: "We chose the pipe, Ma'am." Student B: "Just use the hose." (Students appear to defend their respective opinions.)

(a) (b)

Figure 4. The snapshots from the debate on the selection of water-moving tools.

Figure 4a shows a snapshot of a student defending their opinion by providing logical reasons along with examples. These reasons were eventually agreed upon by other members. He said, "Let's just choose the hose so we can bend it easily."

Figure 4b shows a snapshot of a debate on selecting adhesive/binding tools. One student argued that raffia rope is stronger for connecting hoses. However, other students preferred to choose duct tape because it has adhesive that sticks directly.

Figure 4 illustrates the progression from individual tool selection (4a) to more sophisticated debates about material properties (4b), revealing how the game environment scaffolds increasingly complex argumentation skills. This discussion reflects the growth of argumentation ability, although it still needs to be facilitated with confirmatory questions to deepen the logical reasoning used. The evidence captured in Figure 4 demonstrates that arguing—as one of the Four Cs—emerges organically within the iSTEM-C Game framework when students encounter authentic design challenges requiring collaborative decision-making.

2. **Listening to opinions until completion**
Figure 5 shows snapshots of students listening to a classmate who is speaking. This behaviour marks a crucial developmental shift in collaborative skills, as students begin to recognise that effective problem-solving requires understanding multiple perspectives before taking action. They are starting to learn to fully listen to their friends' opinions, although some still interrupt. The visual evidence in Figure 5 demonstrates the emergent nature of active listening within the iSTEM-C Game context, revealing that this communication skill develops progressively as students engage with collaborative design challenges.

Figure 5. Snapshots of listening to opinions until they finish.

3. **Interpreting problem-solving**
The student doubted the length of the assembled tool; is it long enough to move the water? This spontaneous questioning exemplifies critical thinking, as students learn to evaluate their designs against functional requirements before implementation.
Figure 6 shows a snapshot where students are measuring the length of the assembled tool using their fingers.
Figure 7 shows a snapshot of students ensuring that the bamboo they connected is tightly bound.

Figure 6. A snapshot interpreting the adequacy of the length of the water-moving tools

Figure 7. A snapshot confirming the strength of the water-moving tools bond.

These figures illustrate how the iSTEM-C Game promotes systematic verification processes, encouraging students to test assumptions through hands-on investigation. This initiative demonstrates the ability to interpret problem-solving in a concrete and solution-orientated manner. The progression from questioning adequacy (Figure 6) to confirming structural integrity (Figure 7) reveals how this initiative demonstrates the ability to interpret problem-solving in a concrete and solution-oriented manner.

Question 2
Metrics of collaboration skills

How do students show collaboration during the planning stage?

4. **Self-control/compromise**
   The manifestation of students' self-control is evident in their calm demeanour, non-disruptive behaviour, and ability to remain on the team even when their opinions are not accepted.
   Figure 8 shows a snapshot of collaboration, without imposing the desire to take over what their teammates are working on. The visual evidence in Figure 8 reveals how the iSTEM-C Game structure naturally cultivates compromise skills, as students learn to contribute constructively rather than dominate group processes.

Figure 8. A snapshot of self-control in collaboration.

Question 3
Metrics of communication skills

How do students demonstrate communication skills during the planning stage?

5. **Speaking with clear articulation**
   Students express objections straightforwardly: "If we use pipes, they're hard to bend. Better to just use a hose!"
6. **Stating agreement/disagreement**
   "We chose bamboo, teacher, because it's easier and faster," (welcomed with nods from team members as a sign of agreement).
7. **Responding to friends' opinions**
   Student A: "What should we use to scoop the water?"
   Student B: "Just use a cloth; it absorbs more water."
   Student C: "But it's hard to squeeze out."
   Student A: "Just use a sponge?"
   Student C: "Yeah, if we use a sponge, we can squeeze it with one hand."
   Student: D: "But there's less water."
   This conversation shows the ability to respond with simple sentences.

Question 4
Metrics of creativity skills

How do students demonstrate creativity skills during the planning stage?

8. **Expressing ideas clearly:**
   Students actively proposed ideas, such as the following statement quotes:
   "Because the hose can be bent."
   "We don't need to tie the bamboo, just hold it overlapping, slightly tilted, so the water flows."
9. **Enthusiastic about challenges:**
   Evident from the full involvement of every team member in discussions and tool exploration, showing enthusiasm for completing challenges.
   figures 3 - 8 show enthusiasm, where all students are involved in their groups.
10. **Responsive to diverse thinking:**
   Student A suggests, "Just use the duct tape." Student B adds logical reasoning, "because it can stick directly," which is welcomed with agreeing nods from other members.

4.1.2 The students' performance of the Four Cs during the try and retry stage

The Four Cs performance during the try and retry stage is displayed in Table 5. This table describes the forms of skills identified through actions or utterances in the process of demonstration, evaluation, and reflection.

Table 5. The Four Cs performance at the try and retry stage

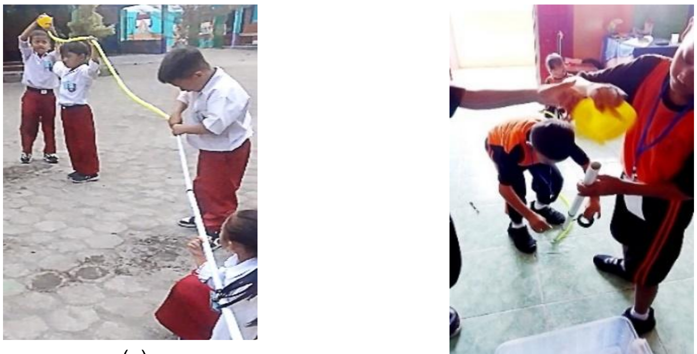
Goal 2	Evaluate students' Four Cs skills performance (critical thinking, collaboration, communication, and creativity) during the 'try and retry' stage.
Question 1	How do students perform critical thinking skills during the try and retry stage?
Metrics of critical thinking skills	1. **Explaining problems** The ability to explain a problem was demonstrated during the exploration phase, particularly when students encountered unexpected situations. These spontaneous explanations reveal how the iSTEM-C Game design prompts students to articulate their thinking processes when confronting authentic engineering challenges.

(a) (b)

Figure 9. Snapshots of problem explanation ability.

Figure 9a illustrates an instance of critical thinking in response to a challenge. A female student remarked, "Attach the mouth of the bottle here" (while bringing the bottle's mouth closer to the edge of the bamboo), "so the water doesn't spill too much."
Figure 9b captures another moment when a student stated, "The hose you're holding should be lifted higher so the water can flow. How can this container be full if the water doesn't flow?"
Figure 9 demonstrates the progression from problem identification (9a) to analytical questioning (9b), illustrating developing critical communication skills essential for collaborative problem-solving.

2. **Reflection**
Students face difficulties and realise that these difficulties should have been avoidable. This awareness is implied in the following statement: "Why did we put that funnel there (upstream)?" We should use the funnel here (the downstream end).
3. **Connecting problems with experience**
The problems encountered by students during the exploration indirectly remind them of previous experiences. This transfer of prior knowledge demonstrates how constructive play environments enable students to apply learnt concepts to novel situations, embodying authentic STEM problem-solving practices.
Figure 10a shows a snapshot where a student tries to prevent a leak by inserting a hose into the pipe because the hose is made of rubber, allowing it to be bent.
Figure 10b shows a snapshot of how students reflexively took duct tape to seal the pipe leak (not choosing rubber bands or strings). This is because they had previous experience with duct tape, finding it easier to use and stickier.



(a) (b)

Figure 10. Snapshots of problem-solving ability based on experience

Figure 10 illustrates the progression from material property recognition (10a) to experience-based tool selection (10b), revealing how the iSTEM-C Game scaffolds critical thinking through meaningful experiential connections.

4. **Making assessments**
After demonstrating the Moving Water Game, students learn about appropriate technology use. This evaluative process exemplifies how the iSTEM-C Game cultivates critical assessment skills, enabling students to judge design effectiveness based on functional criteria.
Figure 11a shows a snapshot of students' evaluation results, that a funnel is not needed to flow water using bamboo. The funnel is used at the collection end to make it easier to pour water in. Figure 11b shows logical evaluation results, where the funnel is combined with a hose to maximise the collection of water squeezed into it. Figure 11 demonstrates the evolution from rejecting unnecessary components (11a) to optimising tool combinations (11b), revealing how iterative assessment within the game framework develops sophisticated engineering judgement

(a) (b)

Figure 11. Snapshots of the evaluation results of appropriate tool usage.

Question 2	How do students perform collaboration skills during the try and retry stage?
Metrics of collaboration skills	**5. Participating in providing help** When Student A asked permission to go to the bathroom, Student B immediately said, "Can I move there to replace him, Ma'am?" (The child remembers the rule about not being able to move places). Other forms of help provided include support given through encouragement, doing what has been agreed upon, and not disturbing what their teammate is working on. **6. Reminding about agreements/reprimanding** When the student was about to break the rules, one of them reminded him, "Don't move forward; you have to stay in place!" When finished playing the game, students appear to work together in tidying up and collecting the equipment that has been used in the classroom.
Question 3	How do students perform communication skills during the try and retry stage?
Metrics of communication skills	**7. Expressing opinions according to context** When the bamboo that has been tied with rubber bands comes loose. Student A: "B, put down the bamboo, then tie it again." Student C: "No! Just let it come loose, it's okay; the important thing is that both bamboos are still held, right? These containers will be full soon; be patient..." Student B: "Okay." From this conversation quote, students show the ability to listen to other people's perspectives in making decisions. **8. Asking questions according to context** Asking questions according to context is more about clarification; for example, when the student in charge of pouring water asks, "How many containers are filled?" or "Why can't the water flow?"
Question 4	How do students perform creativity skills during the try and retry stage?
Metrics of creativity skills	**9. Generate original ideas with creative solutions,** such as using sponges to scoop water. **10. *Developing ideas* reflectively**, Moving the funnel position and changing the technique from tying to tilting the tool demonstrates This adaptive behaviour illustrates how the iSTEM-C Game fosters creative thinking, as students spontaneously modify their approaches when initial strategies prove inefficient. Figure 12 shows creative problem-solving, showing how a group made a mistake in determining tasks. There should be two students at the upstream part, one scooping water, then giving it to the second person to flow it. However, because there's only one person upstream, that person squats down, scoops and pours water into the funnel, then stands up and lifts the end of the hose high so the water flows fast. This improvised solution in Figure 12 exemplifies the creativity

dimension of the Four Cs, demonstrating how constraint-based challenges stimulate innovative thinking within collaborative contexts.

Figure 12. A Snapshot of creative problem-solving

4.1.3 The students' performance of the Four Cs at the show-play stage

The performance of critical thinking, collaboration, communication, and creativity skills during the show-play stage is presented in Table 6. This table outlines the skills identified through the actions and speech of students while demonstrating the construction product "moving water with a relay technique," as well as empirically provable conclusions.

Table 6. The Four Cs performance in the show-play stage

Goal 2	Evaluate the performance of critical thinking, collaboration, communication, and creativity skills during the show-play stage.
Question 1	How are students' critical thinking skills during the show-play stage?
Metrics of critical thinking skills	1. **Presentation of information based on data** Students could explain how the tool works concretely. One student said while demonstrating, "If the tube is twisted or bent, the water can't flow, Ma'am." Another student added, "If the middle part of the hose is too high, the water won't flow. It has to be lower, lower, lower, all the way to the end for the water to flow." This statement demonstrates an understanding of the relationship between height and water flow based on direct experience. 2. **Drawing conclusions** Students' ability to conclude is demonstrated through exploratory dialogue: Researcher: "What shape does the water take when poured into the bottle?" Student: "It takes the shape of the bottle." Researcher: "What if it's in a square jar?" Student: "Just like the shape of the jar." Researcher: "So, what is the shape of water?" Student: "It takes the shape of its container." When asked about the water-scooping tool: Student: "We used a sponge, Teacher." Researcher: "How does a sponge absorb water?" Student: "The water is absorbed, then we wring it out." 3. **Validation** Students demonstrated a concrete understanding of scientific principles, such as moving water with a relay technique, proving that water can be absorbed, flow to lower places, and have a flat surface—all demonstrated directly in front of the class.
Question 2	How do students collaborate when demonstrating their findings?
Metrics of collaboration skills	4. **Taking responsibility for task completion** Tasks within the team were divided and executed according to each member's role. For example, "Student A takes water with a sponge, Student B and C manage the water flow, Student D and E hold the pipe, and Student F holds the container." When one member explains the findings, the others immediately pour water into various containers to strengthen the argument. This reflects collective responsibility and solid teamwork.
Question 3	How do students demonstrate communication skills during the show-play stage?

Metrics of communication skills	5.	**Speaking fluently** Students demonstrated clear articulation and appropriate intonation. When asked, "How was your experience playing the Moving Water Game?", they enthusiastically shared their experiences: "Earlier, I was the one who made the water flow." "I managed to fix the leaking pipe." "Yeah, but I was the one who helped hold the pipe." "Ma'am, my shirt and pants got wet from the water."
	6.	**Scientific communication context** Students are able to effectively communicate their scientific discoveries through demonstrations, explanations, and discussions with peers. They can transform hands-on learning into meaningful verbal expression.
Question 4		How do students demonstrate creativity during the show-play stage?
Metrics creativity skills	7.	**Fluent implementation of ideas** Students demonstrated flexibility in the use of tools. For example, replacing a funnel with a sponge or using their hands to assist the flow of water. They arrange the tools to form a water relay technique, showing that ideas can be effectively applied through collaboration.
	8.	**Enthusiasm for results** The students' enthusiasm was evident through expressions like "Yay! We did it!" and their desire to validate the findings. This reflects a high level of emotional engagement in the learning process.
	9.	**Innovative problem-solving** Students demonstrated innovative problem-solving abilities, such as using a sponge to collect water, arranging bamboo without tying it as a flow path, and inserting a hose into a pipe, although conventionally, a pipe is inserted into a hose.

4.2 Why is the design of the iSTEM-C Game effective in promoting the development of the Four Cs?

The effectiveness of the iSTEM-C Game design in developing the Four Cs is identified through the MDA (Mechanics-Dynamics-Aesthetics) framework. From the MDA design perspective, the Four Cs represent aesthetics that emerge as a result of experiences or skills developed through the application of game mechanics and dynamics.

Table 7. Observation items for the performance of the Four Cs

Goal	To identify and explain how the MDA (Mechanics-Dynamics-Aesthetics) framework works synergistically to promote the development of students' critical thinking, collaboration, communication, and creativity skills.
Question 1	How do the mechanics at each stage of the game determine the dynamics of student interactions?
Matrix of mechanics & dynamics at each stage of the iSTEM-C Game design.	**Planning stage** At the planning stage, students are given the freedom to choose water-moving tools with the condition that all chosen tools must be used. Violating this rule results in the loss of the right to choose again. This mechanism triggers dynamics of discussion, debate, and negotiation, leading to an agreement on tools, design, and implementation. **Try and retry stage** In the Try and Retry Stage, students explore the tools with strict rules—they cannot change positions, and all tools must be used. This creates a team cooperation dynamic in evaluating and reflecting on the design through critical questions. **Show-play stage** The show-play Stage requires students to present their results and answer questions based on their exploration experiences, generating dynamics of proof and scientific conclusion drawing.
Question 2	How do the dynamics formed encourage the aesthetics of students' critical thinking skills?
Matrix of dynamics to encourage critical thinking skills.	Continuous reflection dynamics encourage the development of students' critical thinking skills. When faced with obstacles such as leaks or suboptimal equipment performance, students not only identify the causes but also redesign them to be more effective. They compare the effectiveness of various types of adhesives based on exploration experiences, then choose the alternative that best meets their needs. At the show-play stage, students analyse while verifying exploration results through questions that demand logical and in-depth thinking.
Question 3	Dynamics matrix to encourage communication skills.
Matrices of dynamics to encourage communication skills.	At the planning stage, they present logical reasons and demonstrate the use of tools. During the exploration, students actively listen and respond to the team's opinions. At the show-play stage, they explain their findings based on observations, such as the properties of water that follow the shape of the container and can be moved without a spoon.

Question 4	How do dynamics encourage aesthetic skills in student collaboration skills?
Matrix dynamics to encourage collaboration skills	Students face differing opinions, but they must agree to decide on a joint solution. They work harmoniously, fulfilling their roles as agreed, and help each other overcome technical obstacles. Strong team support reflects the effectiveness of cooperation in achieving game objectives optimally.
Question 5	How do dynamics encourage the aesthetics of students' creativity skills?
matrix dynamics to encourage creative thinking skills.	Providing freedom in tool selection triggers creative exploration. Students create innovative solutions through a combination of tools such as pipes, hoses, and bamboo, and modify designs, such as changing the position of the funnel, selecting alternative materials, and flexibly adjusting the use of tools to enhance the effectiveness of water moving with a relay technique.
Question 6	How does the evaluation of mechanics improve student performance?
Evaluation matrix and changes in the mechanics of the iSTEM-C Game design	**Initial mechanics:** Students are asked to read the game instructions and choose which equipment they will select for the Moving Game. How will they design the equipment? Who is responsible for doing it? **Reaction at school A:** The students appeared passive when directed to discuss which tool to choose for moving water using the relay technique. Each group is dominated by certain students, who are usually very active in class. **Changes in the mechanism implemented at school B:** Presenting a variety of tools in each group and giving them the freedom to choose which tools to use. But the variations are limited (for example, when students choose bamboo, bamboo pieces will be provided) as well as the tools to attach them. **The reaction of students at school B:** The variety of equipment available on the students' desks makes them more enthusiastic. The discussion becomes more lively because each student has their own preferences in determining which tools should be chosen. The presence of tools encourages discussions on selection, usage, and implementation of the results in each group. In the demonstration process, students' creativity is less apparent because their tools and designs seem to be similar. **Students' reactions at school B** The availability of various tools at each group's table increased the students' enthusiasm. Discussions among students became more active because each individual had their own preferences in determining which tools to use. The presence of these tools also encourages interaction regarding the selection, use, and application of results within each group. However, the students' creativity has not yet appeared optimal because the choice of tools and the designs produced tend to be uniform. For example, when group A chooses pipes as the main component, other groups are encouraged to select the same tool, thus limiting the diversity of ideas. **Change of mechanism at school C** To encourage originality and design variation, the implementation mechanism was changed. At School C, various tools are provided at the front of the classroom, and students are given the freedom to choose as many tools as they need and in as much variety as possible. However, a rule is applied that all the selected tools must be used in the design process. If this rule is violated, the group loses the opportunity to evaluate their water-moving design. It is not entitled to receive the award in the form of a star sticker. **Reactions of students at school C** Students showed high enthusiasm; most appeared eager to express their ideas. Although some students tended to be quiet, they still listened attentively to the ideas presented by their peers. The students' initial enthusiasm led to a desire to use all the available equipment. However, the implementation of rules made them more careful and selective in choosing the most suitable tools for creating designs. **Implications for school D** No specific records were found regarding the implementation mechanism of the iSTEM-C Game design at School C. Therefore, the same mechanism was applied at School D. The results showed a similar student response to that observed at School C, both in terms of enthusiasm, discussion engagement, and attitudes in choosing tools.

Based on the evaluation results of the mechanics aspect, the final design of the iSTEM-C Game is presented in Table 8. The table displays the MDA framework tested on early elementary school students, encompassing three core elements: mechanics, dynamics, and aesthetics.

Table 8 demonstrates how each mechanical component directly influences dynamic interactions and aesthetic experiences. For instance, player configuration and resource selection shape collaborative behaviors and problem-solving strategies. This integration validates how the MDA model operationalises constructive play principles for STEM learning while fostering the development of the Four Cs (Communication, Collaboration, Critical thinking, and Creativity).

Table 8. STEM-integrated constructive game design with MDA framework.

Mechanics	Dynamics	Aesthetics
Players • Ages 8-9 years • 4-6 people per group **Tools and resources:** 3 pipes of different sizes, 3 pieces of hose @ 1 meter each, 3 bamboo sections, raffia string, rubber bands, adhesive tape, thread, fishing line, water funnel, sponges, various containers, napkins, water. **Rules:** • Each team is free to choose from the available tools. However, all selected tools must be used to move the water. • The position of predetermined containers must not be changed. • The provided containers must be filled to the marked line. **Obstacles:** • Moving the water must be performed without stepping from the designated team position.	**Planning stage** • Students conduct group discussions to discuss the tools to be used, tool usage strategies, and task distribution. **Try and retry stage** • Students explore the selected tools and create designs for water-moving tool usage. • Students conduct evaluation and reflection on the success/failure of tools and designs. • Students redesign problem-solving approaches based on evaluation/reflection results. • Students demonstrate or test designs and try again. **Show-play stage** • Demonstration of moving the water techniques without stepping. • Conclude the properties of water.	**Social interaction:** • Plan problem-solving design together. • Collaboration among team members. • Communicate clearly and listen to one another. • Create problem-solving designs creatively.

The design of the iSTEM-C Game is also represented in the form of game instructions, as visualised in Figure 13. This instruction provides student-accessible guidance that scaffolds independent gameplay or is utilised by teachers as a guide in facilitating the playing process.

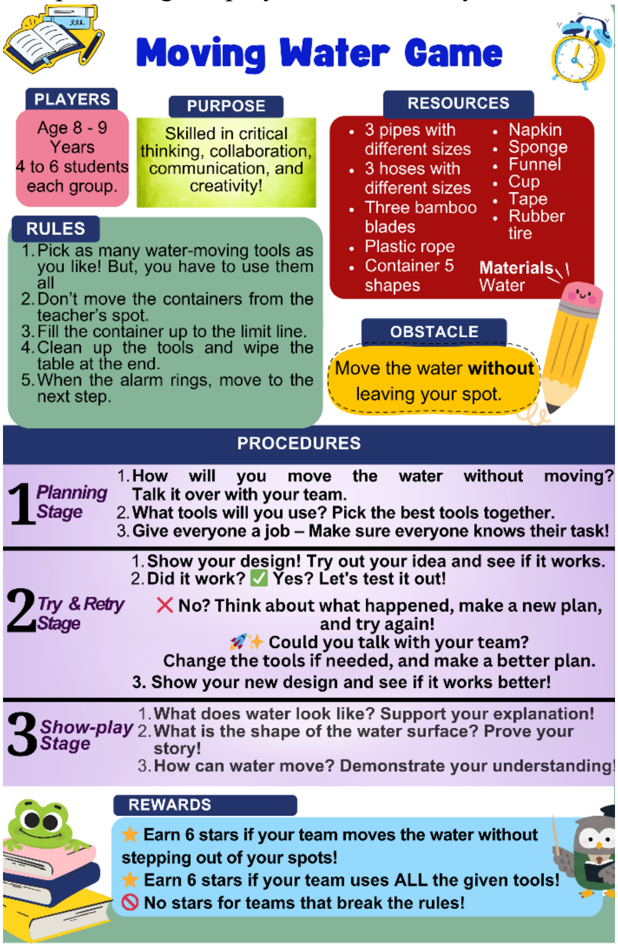


Figure 13. Instructions for the moving water game demonstrates how the three-stage structure translates into clear procedural steps, enabling autonomous student engagement

The effectiveness of the iSTEM-C Game design in promoting Four Cs skills has been defined using the Mechanics-Dynamics-Aesthetics (MDA) framework and presented through game instructions. Observational data confirm the success of this design approach. When game mechanics are systematically evaluated, the percentage of Four Cs performance increases correspondingly.

Table 9 illustrates this progression clearly. The table demonstrates a consistent upward trajectory in student performance across all thirty metrics from School A to School D. This pattern reveals a direct alignment between refined game mechanics and the proportion of Four Cs improvement in each school. Notably, Schools C and D achieved markedly higher performance levels, with percentages ranging from 57% to 88%. These results substantiate the claim that well-designed game mechanics directly enhance Four Cs development.

Table 9. Students' Four Cs improvement percentage

N0.	iSTEM-C Game Stages	Observation items for the performance of the Four Cs	Percentage of occurrence for each item			
			A (n=21)	B (n=28)	C (n=24)	D (n=25)
1	Planning stage	Listening to others' opinions until completion	29%	57%	71%	72%
2		Interpreting problem solutions	29%	54%	71%	76%
3		Debating	29%	61%	73%	76%
4		Explaining problems	29%	54%	71%	68%
5		Reflecting	29%	57%	67%	65%
6		Assessing/evaluating	29%	57%	78%	75%
7		Connecting problems with experience	38%	50%	76%	72%
8		Validating	33%	57%	72%	76%
9		Drawing conclusions	33%	64%	86%	88%
10		Conveying information based on data	33%	61%	86%	85%
11	Try and retry stage	Self-control/compromise	38%	46%	71%	76%
12		Participating	33%	46%	87%	84%
13		Reminding about the rule	38%	46%	67%	68%
14		Complying with agreements	29%	43%	65%	67%
15		Being responsible	33%	43%	62%	68%
16		Speaking with clear articulation	33%	46%	67%	70%
17		Listening to others' perspectives	29%	43%	57%	64%
18		Expressing opinions according to context	38%	43%	62%	68%
19		Asking questions according to context	42%	46%	81%	76%
20		Expressing agreement or disagreement	46%	46%	67%	64%
21		Responding to friends' opinions	29%	50%	67%	68%
22		Speaking fluently	29%	43%	67%	70%
23		Expressing ideas clearly	38%	54%	76%	80%
24		Being enthusiastic about challenges	38%	50%	78%	82%
25	Show-play stage	Being responsive to diverse thinking	42%	57%	86%	84%
26		Generating original ideas	25%	54%	61%	68%
27		Being brave to explore the unknown	33%	50%	71%	76%
28		Modifying ideas.	29%	46%	76%	73%
29		Being fluent in implementing ideas	33%	46%	67%	71%
30		Being enthusiastic about results	29%	43%	75%	80%

5. Discussion

Game mechanics significantly influence the performance of the Four Cs during the implementation of the iSTEM-C Game design. This finding is reinforced by the evaluation of game mechanics and the subsequent enhancement of Four Cs performance. The diverse tools provided serve a purpose beyond mere technology within the STEM context or equipment within the constructive play framework. Instead, they function as cognitive stimuli for students in the concrete operational stage, whose understanding remains dependent on real-world experiences.

Game mechanics at the planning stage play a crucial role in determining game dynamics. These dynamics subsequently influence aesthetic aspects manifested through students' critical thinking skills, collaboration, communication, and creativity. Three key components of mechanics emerge at this stage: (1) the diversity of tools presented directly to students before discussion, (2) rules embedded with real-world problems and communicated to participants, and (3) challenges appropriately tailored to students' cognitive capacity.

Providing diverse tools constitutes a form of facilitation appropriate for the concrete operational thinking stage. This is evidenced by students' tendency to initially select tools based on individual preferences, such as shape, colour, or personal interests. The availability of various tools encourages student interaction with both objects and peers, thereby stimulating argumentative and collaborative processes in reaching consensus on the most suitable tool to solve the presented challenge.

This pattern aligns with Piaget's theory of cognitive development. Piaget asserts that the understanding of students aged 7–11 years is highly dependent on real-world experiences and direct exploration with objects in their surrounding environment [5], [26]. Recognising this developmental characteristic, the iSTEM-C Game design is structured with specific challenges and rules to scaffold meaningful exploration.

The challenges and rules of the game constitute essential elements of the learning framework. Without both components, the game risks losing its fundamental essence as a meaningful learning experience [33]. In the Moving Water game, students are challenged to move the water from one point to another using a relay technique, wherein students are prohibited from changing positions. They may choose and utilise as many tools as desired, but they must employ all selected tools.

Violations of the rules result in sanctions, such as losing the opportunity to win prizes or losing the chance to replace equipment after evaluation. This mechanism raises awareness of consequences and directly encourages students to think critically to make informed decisions. Thus, the discussion moments during the planning stage become active. The students debated to defend their opinions to avoid consequences.

The quality of preparation during the planning stage is demonstrated in the Try and Retry stage, where students test their tools, designs, and individual roles in the task of moving water without moving themselves. As unexpected challenges emerge, students engage in open reflection and critical evaluation of their designs and tools.

This openness stems from the fundamental principle of the iSTEM-C Game design: students are permitted to replace tools, redesign, and attempt solutions as many times as desired. Although there are requirements that must be met—namely, not violating the established rules—this approach actually strengthens confidence in conveying ideas and reflection results. For example, students become capable of answering questions such as "Why was this tool chosen?" or "How effective is it compared to the previous tool?"

This mechanic differs substantially from the Tinkering-based STEM approach. Both iSTEM-C Game design and Tinkering-based STEM approaches fundamentally emphasise product design and simple technology exploration. However, STEM-based Tinkering involves progressive increases in both the complexity of products produced and the complexity of technology utilised [9].

Research results indicate that Tinkering-based STEM positively impacts students' psychomotor, cognitive, and affective skills. However, approximately one-third of students with learning difficulties felt frustrated and had decreased motivation. This finding aligns with the perspectives of Whiting, who stated that frustration can exacerbate learning challenges and negatively impact students' educational experiences [38]. Therefore, maintaining an appropriate balance between the level of difficulty and students' cognitive capacity is crucial for optimizing the learning process.

The iSTEM-C Game design demonstrates appropriate alignment between the cognitive capacity of early elementary school students and the difficulty level of the challenges presented. Repeated exploration deepened students' understanding and reflective abilities, encourages students to gradually design and test water-moving systems based on the results of evaluation, reflection, and mutual agreement.

Technology in the iSTEM-C Game design, although diverse, remains contextual to problem-solving activities. Bamboo, PVC pipes, and hoses are presented in varying quantities and sizes. These materials do not preclude the complexity of design configurations students create to move water. However, this complexity is determined by the students themselves. This approach aligns with the principles of constructive play, which emphasize the manipulation, construction, and integration of elements as strategies for generating effective solutions [18], [30], [31].

Ultimately, the show-play stage represents the culmination of the activity. During this stage, students present the success of their water-moving design using a relay technique. Direct experience and repeated exploration contribute to the formation of equilibrium, a stable mental state where an individual can handle new information or experiences using existing cognitive schemas [26]. This phenomenon was evident when students understood that the bamboo pieces didn't need to be tied for the water to flow, as long as they were arranged correctly. The funnel is more efficient when placed upstream rather than downstream.

These events align with Dewey's experiential learning theory, which positions exploration and reflection as critical components of meaningful learning [28], [39]. During exploration, students actively engage in constructing knowledge, while reflection provides opportunities to critically evaluate, strengthen, and solidify their understanding.

Overall, the iSTEM-C Game design demonstrably shows its mechanics effectively driving the performance of the Four Cs. However, to strengthen the generalization of these initial findings, further research is needed. A quantitative approach would enable more precise measurement of effectiveness and allow comparison with other STEM learning models implemented in early primary education.

6. Conclusions

The performance of the Four Cs among students in the implementation of the iSTEM-C Game design is significantly influenced by game mechanics that emphasise the provision of various tools for direct problem-solving presented to students. The rules and challenges embedded in the mechanics of equipment utilization serve as catalysts that encourage students to communicate, think critically, collaborate, and demonstrate creativity.

The Mechanics, Dynamics, and Aesthetics (MDA) framework in the iSTEM-C Game design serves as a conceptual reference that offers a novel approach in the implementation of STEM integrated with constructive play. This approach has not been previously applied. This research makes a significant contribution to enriching the literature on the integration of STEM and non-digital games, particularly the implementation of constructive games, which have thus far generally been limited to the use of blocks or Lego. Furthermore, constructive play can actually utilise a variety of contextual tools, which have been very limitedly studied in the context of early primary school education.

In addition, this research provides three other significant contributions: (1) presenting a STEM learning approach that is adaptive to the concrete operational cognitive development stage of early elementary school students; (2) providing a syntax for educational games based on the empirically tested MDA framework; and (3) offering a practical pedagogical framework for teachers to develop students' Four Cs skills.

However, this study has several limitations. First, the materials used are limited to the topics of "properties of water" and "non-standard measuring instruments"; therefore, the effectiveness of this approach on other subject matters has not yet been determined. Second, the duration of observation was limited to just one play session, making it impossible to monitor the continuous development of students' skills over time. Third, the narrow geographical scope—limited to four elementary schools in Sleman Regency—restricts the generalizability of the findings.

Therefore, further research is recommended to implement the iSTEM-C Game design by expanding the scope of subject matter and extending the duration of the intervention to enable longitudinal evaluation. Additionally, expanding the geographical area is also important to enrich the representativeness of the findings. A comparative quantitative approach is highly recommended, particularly through comparisons with the STEM approach based on Project-Based Learning (STEM-PBL) focused on early elementary school students.

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Conflicts of interest

The authors state that there is no conflict of interest.

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