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Interdisciplinary STEM education foundational concepts: Implementation for knowledge creation

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Abstract

Interdisciplinary thinking is essential to understanding and solving real-life problems and requires multiple disciplinary viewpoints. Research into STEM education highlights that it promotes an interdisciplinary learning process integrating science, mathematics, engineering, and mathematics knowledge and skills. However, STEM definitions are varied, and implementation recommendations are scant, resulting in diversity in the development and implementation of the learning process. This study critically analyses the literature to determine the fundamental concepts of STEM education and STEM discipline integration. Our analysis discovers six key components of STEM education, encompassing the integration of discipline, utilization of multiple representations, engagement with realistic and relevant problems, application of the engineering design process, encouragement of active collaboration, and emphasis on student-centered learning approaches. Then, we transform these key components to a practical learning process. The STEM-DTaM (STEM with Design Thinking and Makerspace) learning model consists of seven steps. We then unfold how this proposed learning could facilitate interdisciplinary thinking construction.

Keywords: STEM foundational concepts, interdisciplinary thinking, interdisciplinary learning, STEM Education, design thinking, makerspaces

INTRODUCTION

Interdisciplinary thinking is essential. Interdisciplinary thinking is the capacity to integrate knowledge and modes of thinking of two or more disciplines to produce a cognitive advancement in ways that would have been impossible or unlikely using only one disciplinary approach (Mansilla, 2005; Mansilla & Duraising, 2007; Spelt et al., 2009). In the real world or the workforce, disciplines do not define problems (English, 2016; Glancy & Moore, 2013; Herschbach, 2011); our brains think holistically (Spiller, 2017) to understand and solve problems. The complexity of world issues necessitates an interdisciplinary approach to solution generation (Clark & Wallace, 2015; Newell, 2007; Power & Handley, 2019; Syahril, 2019). Thinking skills from across disciplines help to understand daily experiences such as sustainability problems (Bestelmeyer et al., 2015), astrobiology phenomena (Cockell, 2002), environmental interaction (Tan & So, 2019), climate change and world poverty (Golding, 2009), or even to interpret a work art in a new medium (Mansilla, 2005). Interdisciplinary thinking skills lead to more comprehensive, sophisticated, and advanced understanding.

Interdisciplinary learning opportunities are required to facilitate the construction of interdisciplinary thinking. Students require assistance synthesizing two or more disciplines (Glancy & Moore, 2013; Spelt et al., 2009). Finding connections, identifying commonalities, and evaluating diverse methods, presumptions, and values from each discipline construct interdisciplinary thinking (Hursh et al., 1983). Since each discipline has different disciplinary thinking (Gesthuizen et al., 2020), different worldviews, vocabularies and assumptions (Davies & Devlin, 2007), integrating multiple perspectives across disciplines is challenging for students.

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Contribution to the literature

- The study synthesises five seminal papers to determine foundational concepts of STEM education.
- The study discusses design thinking and makerspace implementation of the foundational concepts.
- To facilitate the construction of interdisciplinary thinking, the study provides a conceptual framework of a STEM education learning model.

In describing the characteristics of the learning process to construct interdisciplinary thinking, Spelt et al. (2009) identified six learning process conditions that enable interdisciplinary thinking. The first four conditions are gradual advancement, linear, iterative, and milestones with encountering questions to nurture interdisciplinary thinking development. The remaining conditions aim to achieve interdisciplinarity and reflection. Regarding the learning process, Newell (2007) identified drawing (critically) on disciplinary perspectives and integrating their insight to construct a more comprehensive understanding. Spelt et al. (2009) and Newell (2007) describe interdisciplinary thinking as constructed through a steady and progressive process, beginning with all relevant disciplinary perspectives as the focus, then confronting and integrating their insights to obtain an interdisciplinary view as a comprehensive understanding and solution to solve the problem.

STEM (science, technology, engineering, and mathematics) education is a well-known example of interdisciplinary learning that dismantles the conventional barriers between the disciplines (Jolly, 2017; Sahin, 2015; Vasquez et al., 2013). By integrating the disciplines, STEM education provides opportunities to learn and address relevant real-world problems (Bybee, 2013; English, 2016; Glancy & Moore, 2013; Sahin, 2015; Timms et al., 2018; Vasquez et al., 2013). Hence, STEM education facilitates the construction of interdisciplinary thinking.

In the last two decades, STEM has attracted the attention of many educational systems (Council, 2014; Ng et al., 2022) and has become an educational focus in many countries (Timms et al., 2018). Özkaya (2019) explored the global trend in STEM research between 1992 and 2017, noting the number of publications on STEM research increased significantly in the latter five years, with the United States, England, and Australia as the top three publishing nations. Li et al. (2020) reported a significant growth in STEM research in the last three years of their 2000 to 2018 review, with the top ten countries representing almost all continents or regions except Africa. Similarly, in developing countries, such as southeast Asian nations, Thao et al. (2020) showed that STEM education research dramatically increased in the last three years from 2000-2019. In Indonesia, for instance, as the largest country in southeast Asia, STEM education research has increased in all levels of education from 2015-2020 (Farwati et al., 2021), including in higher education institutions (Nugraha et al., 2023). The finding demonstrates that STEM education has grown in developed and developing nations, indicating the broad opportunities to construct interdisciplinary thinking.

However, as STEM rapidly spreads and grows, its definition has varied. STEM is not a well-defined field, unlike science discipline-based fields such as physics, biology, chemistry, and mathematics (Li et al., 2019). Hasanah (2020) describes four definitions of STEM: as a discipline, as instruction, as a field, and as a career. The STEM acronym has been used as a label for any event, program or activity involving one or combination of the four STEM disciplines, resulting in a lack of clarity and substantive meaning (Bybee, 2013; Vasquez et al., 2013). The STEM acronym expanded to include other disciplines and focuses, such as STEAM ("A" for the Arts), STREAM ("R" for Reading and wRiting), STEMM (additional "M" for Medicine), and steM (capital "M" to indicate Mathematics as the focus) (Tan & Kidman, 2021).

Various interpretations manifest for integrating STEM disciplines, wherein many advocate for disciplinary integration to equip students with skills to solve multidisciplinary problems. Others express skepticism due to insufficient content coverage and limited conceptual development (English et al., 2020). Concerns arise regarding identifying disciplines in the epistemic mix, "in practice and in principle" (Tytler et al., 2021). Moreover, challenges arise in establishing connections between facts and phenomena in education systems where subjects are kept fragmented and emphasize disciplinary content. The integration of real-life contexts is frequently absent (Hursh et al., 1983; Scheer et al., 2012; Spiller, 2017). Scheer et al. (2012) reveal a missing link between theoretical insights from pedagogical science and their practical implementation in interdisciplinary teaching, leading teachers to face challenges and negativity in their classrooms due to a lack of clear procedural guidance. Insufficient knowledge and preparation to implement STEM education contribute to dissatisfied teaching STEM experiences (Jho et al., 2016) and reluctance to adopt STEM learning (Nadelson et al., 2013) in their classrooms. Hence, a more explicit and well-defined STEM learning process is required to facilitate the construction of interdisciplinary thinking.

In this study, we bring the Indonesian context to the fore for three reasons. First, our past work (Nugraha et al., 2023) indicates that Indonesian academics have perspectives on what STEM education is and how STEM education is implemented in the curriculum. The perspectives differ from those found in the research literature, for example, the integration of STEM disciplines in the learning process can be seen as a method to explore and comprehend a phenomenon or concept using each STEM subject, as a learning syntax consisting of S-T-E-M processes sequentially, and as an interdisciplinary spaces that combines STEM disciplines to address a problem. This broad interpretation could confuse adopting, developing, and implementing STEM education, including facilitating interdisciplinary thinking construction. Second, there is a lack of literature on constructing interdisciplinary thinking through STEM education. Although STEM education is considered to provide interdisciplinary learning, no one study exists that focuses on constructing interdisciplinary thinking in the Indonesian context (Nugraha et al., 2023). Third, the new curriculum in Indonesia–the emancipated curriculum, "kurikulum merdeka"–provides the opportunity for interdisciplinary learning at all levels of education. In the school setting, the Ministry of Education, Culture, Research, and Technology (MoECRT) of Indonesia mandates that all subjects at all school levels conduct project activities–the "projek penguatan profil pelajar pancasila (P5)" or the project to strengthening pancasila student profile–and requires projects are implemented collaboratively across disciplines (MoECRT, 2022). The new curriculum mandates each subject to allocate 20% (elementary school), 25% (secondary school), and 30% (high school) of their total lesson hours to undertake the P5. In a higher education setting, students can take courses outside their study program based on their interests for three semesters to enrich and improve their knowledge and competence in the real world (MoECRT, 2020). Hence, constructing interdisciplinary thinking through STEM education is facilitated by the curriculum structure in the Indonesian context. Furthermore, since Indonesia is a large country with a diverse cultural population–the fourth most populous nation in the world with more than 300 ethnicities–, our work offers a recommendation for a global readership. In this paper we propose a STEM education learning model as an interdisciplinary learning model to facilitate the construction of interdisciplinary thinking.

We provide a theoretical analysis translated into practical learning guidance from which we explore two research questions:

RQ1. What are the foundational concepts of STEM education?

RQ2. How can STEM education be implemented to facilitate interdisciplinary thinking construction?

This study contributes to the literature by investigating the potential of STEM education in promoting the construction of interdisciplinary thinking.

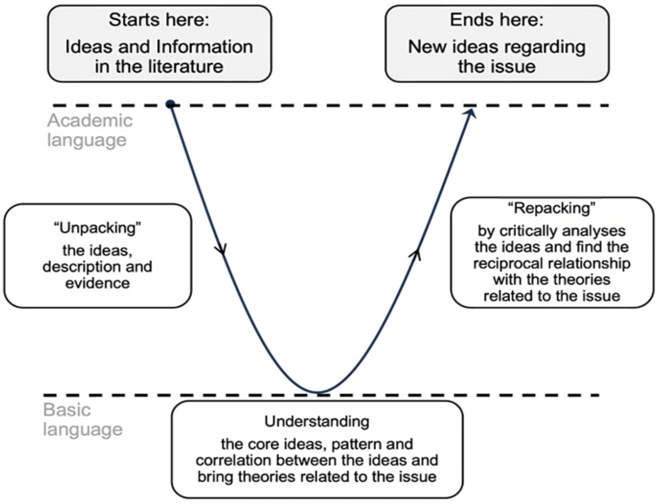

Figure 1. The semantic wave of the critical analysis process (adapted from Brooks & Kenny, 2022)

METHODS

We have systematically explored the mapping of the STEM education literature, drawing on ProQuest Education database, 14 international STEM education journals and 54 Indonesian best-ranking journals (see Nugraha et al., 2023). In the context of interdisciplinary thinking, although scholars recognize STEM education's interdisciplinary nature encompassing the four STEM disciplines, there is still limited information on how STEM education contributes explicitly to the cultivation of interdisciplinary thinking. Our critical analysis of the literature revealed a diversity of perspectives regarding the conceptualization and implementation of STEM education. Browne and Keeley (2007) describe critical analysis as a systematic process of deconstructing information rationally and logically. This process extends beyond simple description and analysis; it necessitates evaluation, critique, and the generation of insights based on the processed information. Similarly, Brooks and Kenny (2022) illustrate critical analysis as a "repacking" process within the semantic wave to understand academic information and provide new information or ideas (see **Figure 1**). Start by unpacking the information, exploring the evidence and examples, understanding core ideas, patterns, and correlations between them, and then repacking the information critically, considering related ideas and theories to provide new knowledge.

In addressing the research questions, we examined our corpus to identify foundational concepts of STEM education. We analyzed the ideas associated with each concept, extracting and organizing the core ideas into a matrix to reveal connections and similarities. This systematic process identified the foundational concepts of STEM education (**RQ1**). Addressing **RQ2**, we further

Table 1. STEM education aspects and components

STEM components	Aspects of advancing STEM education (Bybee, 2010)	Aspects of STEM learning environments (Glancy & Moore, 2013)	STEM guiding principles (Vasquez et al., 2013)	Aspects of advancing integrated STEM learning (English, 2016)	Criteria for STEM programs (Jolly, 2017)
1	Highlight the significance of science, closely linked with technology and engineering	Integration	Focus on integration	Making STEM connection more apparent	-
	Increase the emphasis on technology			Lifting the profile of mathematics in STEM integration	
	Integrate curricular to explore recent real-life challenges				
2	-	Multiple representations	"Mix it up" by providing a variety of outcomes	-	Use a variety of communication
3	Integrate curricula to explore recent real-life challenges	Personal experience	Establish relevance	-	Solve real-world problems or engineering challenges
		Realistic problem			Introduces STEM Careers and or life applications
4	Increase the recognition of engineering	-	-	Lifting the profile of engineering in STEM integration	EDP
					Appreciate a failure in the design process
5	Emphasize 21st century skills	The collaborative nature of STEM	Emphasize 21st century skills	-	Teamwork
6	-	-	Challenge students by using grade-level-appropriate challenges	Targeting student outcomes	Standard, appropriate and applied science and mathematics content
					Inquiry-based, student-centered learning

explored the literature for STEM implementation fostering interdisciplinary thinking by considering the characteristics of the interdisciplinary learning process and cognitive maturation processes.

RESULT AND DISCUSSION

We present the results and discussion in two sections to address each research question. We commence with critical analysis results on the foundational concepts of STEM education. Then, we move towards a conceptual framework of the STEM education learning model to facilitate interdisciplinary thinking construction.

What Are the Foundational Components of STEM Education?

Five authors are leading the advancement of STEM education:

- Bybee (2010) suggests five aspects to advance STEM education beyond a slogan (1,842 citations).
- Glancy and Moore (2013) provided five theoretical foundations for STEM learning environments based on the theories of Dewey, Dienes, and Lesh (98 citations).
- Vasquez et al. (2013) established five STEM guiding principles to conduct and develop STEM lessons (722 citations).
- English (2016) recommended four aspects to advance STEM as integrated learning (1,313 citations).
- Jolly (2017) introduced eight criteria for developing STEM programs and learning practices (114 citations).

While these five authors address distinct components of STEM education, our analysis reveals the underlying ideas exhibit interrelatedness, convergence, and mutual reinforcement in the context of implementing and advancing STEM education, especially within the domain of pedagogical practice. We found similarities within these components (see Table 1).

Our analysis determined six foundational components of STEM education. We developed the STEM-IMREAL framework to advance and develop STEM learning from this. As shown in Figure 2, the STEM-IMREAL model identifies the following components:

- **I**ntegrating disciplines. STEM disciplines are integrated (Bybee, 2010; Glancy & Moore, 2013) with

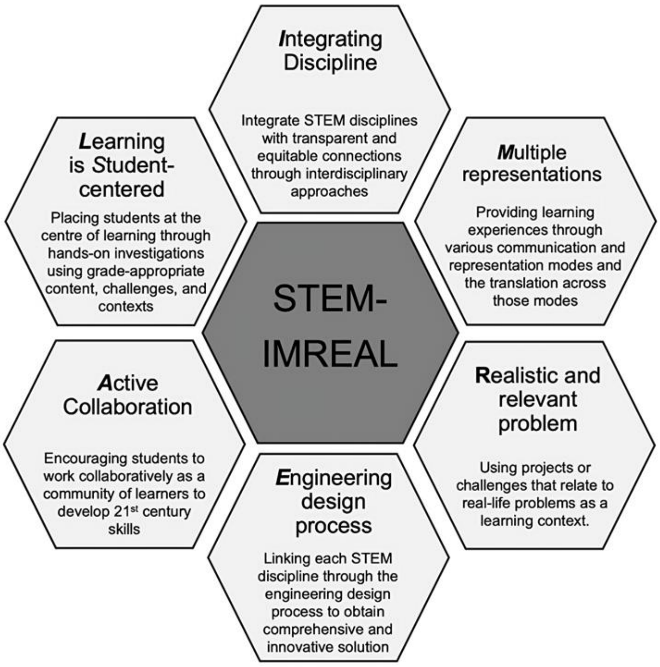

Figure 2. STEM-IMREAL components (Source: Authors' own elaboration)

transparent and equitable connections (English, 2016) through interdisciplinary approaches (Vasquez et al., 2013).

- **M**ultiple representations. Provide learning experiences with various communication and representation modes (Jolly, 2017; Vasquez et al., 2013) and the translation across those modes (Glancy & Moore, 2013).
- **R**ealistic and relevant problems. Use projects or challenges (Glancy & Moore, 2013) that relate to real-life problems (Bybee, 2010; Glancy & Moore, 2013; Jolly, 2017; Vasquez et al., 2013) as a learning context.
- **E**ngineering design process (EDP). Link each STEM discipline through the EDP (English, 2016) to solve problems innovatively (Bybee, 2010), which consists of defining problems, researching/gathering information, imagining possible solutions, planning, creating, testing and evaluating the solutions, redesigning, and communicating solutions (English, 2016; Jolly, 2017).
- **A**ctive collaboration. Encourage students to work collaboratively as a community of learners (Glancy & Moore, 2013; Jolly, 2017; Vasquez et al., 2013) to develop 21st century skills (Bybee, 2010; Vasquez et al., 2013).
- **L**earning is student-centered. Place students at the center of learning (English, 2016; Jolly, 2017) through hands-on investigations using grade-appropriate content, challenges, and contexts (Jolly, 2017; Vasquez et al., 2013).

The term "IMREAL" (pronounced: I'm real) symbolically describes STEM education, prioritizing real-life contexts in the student-centered learning process that prepares students to be competent future citizens. The nomenclature change to IMREAL from our earlier work (see Nugraha et al., 2023) is perceived as more functional and similar to the rationale behind the changes of the STEM abbreviation itself, from SMET to METS, eventually becoming STEM (Bybee, 2013).

Integrating disciplines

The first foundational concept of STEM learning is the integration of the science, technology, engineering, and mathematics disciplines. Glancy and Moore (2013) highlight integration enhances problem comprehension through rich, captivating, and meaningful experiences in natural and realistic conditions. Vasquez et al. (2013) note discipline integration assists students in identifying the interconnectedness of concepts, linking fragmented information, and encouraging broader thinking to produce innovative and creative solutions. English (2016) recommends nurturing generic skills, such as 21st century skills, problem-solving, critical thinking, creativity, and innovation. STEM education has to advance integration by lifting the profile of all its disciplines and their interdisciplinary connections. To enhance STEM education, Bybee (2010) recommends emphasizing the importance of science and, by extension, highlighting technology and engineering to undertake challenges of real-life relevance. Hence, in STEM IMREAL, we propose integrating STEM disciplines with more transparent and equitable connections as an essential aspect of effective STEM learning.

Multiple representations

Two crucial components of STEM education are allowing students to communicate their ideas in multiple ways and offering them multiform experiences. Glancy and Moore (2013) indicate that students' interactions affect their current experiences, and current experiences affect their future experiences. Thus, the teacher's role is to give students various experiences that are creatively relevant to their future experiences. In the STEM context, the provision of this experience gives opportunities for students to express and share knowledge, expertise, results and skills through various communication approaches (Jolly, 2017), outcomes (Vasquez et al., 2013), and representations (Glancy & Moore, 2013). The representation could be a written report, symbol, diagram or picture, concrete models, experience-based metaphors, and spoken language. Glancy and Moore (2013) suggest that to gain conceptual understanding, students should experience various representations and translations between these representations. Therefore, we propose that using multiple representations by providing a learning experience with various communication approaches and translations between these representational modes is foundational to STEM learning.

Realistic and relevant problem

Problems in STEM learning involve perspectives and knowledge across disciplines. The problems must be complex enough to represent issues that students might face in their personal lives (Glancy & Moore, 2013), thus highlighting the relevance and usefulness of STEM learning (Vasquez et al., 2013). The problem is not a fragmented problem of science, technology, engineering, or mathematics; instead, it is an interdisciplinary issue where the learning and knowledge are used from various disciplines while investigating and solving the problem. Topics in STEM education focus on real-world problems or engineering challenges (Jolly, 2017) (e.g., energy efficiency, resource utilization, environmental quality, and hazard mitigation) that students as citizens need to understand and address (Bybee, 2010). Glancy and Moore (2013) mentioned that the problem in STEM learning should be realistic, feasible, and believable so that the student feels a personal experience and connection to the context. Hence, to conduct integrated STEM teaching effectively, using realistic and relevant issues or projects that relate to real-life problems as a learning context in which students see the purpose of engaging in them is foundational.

Engineering design process

The EDP is essential to integrate each STEM discipline into STEM learning. EDP is systematic, orderly, and open-ended for addressing problems and generating solutions (Jolly, 2017). Jolly (2017) describes eight EDP steps: defining the problem, researching, imagining, planning, creating, testing and evaluating, redesigning, and communicating the solution. Failure is a natural part of the EDP and essential to creating an improved or successful solution. English (2016) identified three components of the EDP process: defining problems, generating and evaluating several solutions, and optimizing the solution. Despite having distinct EDP steps, the process is iterative. In STEM learning, students employ this process to create a model, prototype, or product that they believe could address their problem or challenge. Hence, we suggest adopting the EDP by defining problems, researching/gathering information, imagining the possible solution, planning, creating, testing and evaluating, redesigning, and communicating the proposed solution.

Active collaboration

Glancy and Moore (2013) observed that real-world interdisciplinary challenges are commonly addressed collaboratively by diverse teams, leveraging expertise. It is advantageous for students to work collaboratively, fostering a collective learning environment. Vasquez et al. (2013) argue workforces require robust teamwork and collaboration skills, along with 21st century competencies, such as critical thinking, problem-solving, creativity, and effective communication. Bybee argues that active student engagement in STEM Education fosters the development of 21st century skills, including adaptability, complex communication, social skills, non-routine problem-solving, self-management, and system thinking (Bybee, 2010). Students must engage in active collaboration. They need to engage in team-based activities, which assist in devising, creating, and refining prototypes and products, followed by rigorous testing and analysis to enhance the proposed solutions (Jolly, 2017). Hence, working collaboratively as a community of learners and learning from each other is foundational to STEM learning.

Learning is student-centered

Positioning students as the focal point of learning constitutes the fundamental essence of STEM learning. STEM education aims to equip students with the requisite knowledge, attitudes, and life skills essential for their future roles as active citizens; consequently, the educational approach should refer to student-centered activities (English, 2016; Jolly, 2017). Students undertake activities through an inquiry-based approach with hands-on investigation (Jolly, 2017). The tasks, content, context, challenges, and problems should align with students' abilities (Jolly, 2017; Vasquez et al., 2013). Challenges should not be simplistic, which may lead to disengagement, nor overly complicated, causing students to lose motivation. Hence, in STEM IMREAL we suggest placing students at the learning center, the foundation for STEM learning.

How Can STEM Education Be Implemented to Facilitate Interdisciplinary Thinking?

In our critical analysis of the literature, we found STEM education to be associated with design thinking and makerspaces. Design thinking, a human-centered process to solve real-life problems, provides experiences integrating disciplines and employing the EDP in addressing a real-life problem. Makerspace activities are powerful learning spaces to create artefacts that facilitate active student-centered learning collaboration and provide multiple-representation experiences. **Figure 3** inserts design thinking and makerspaces into the IMREAL foundational components. Integration, engineering design and realism align with design thinking, whilst multiple representation, active collaboration and learning that is student centered (MAL) aligns with makerspaces. In what follows, we describe these components' characteristics and why they enrich STEM education.

Design thinking process

Design thinking was initially introduced in the business and engineering field (Donar, 2011; Dorland, 2022) to create an innovation or enhance the value of

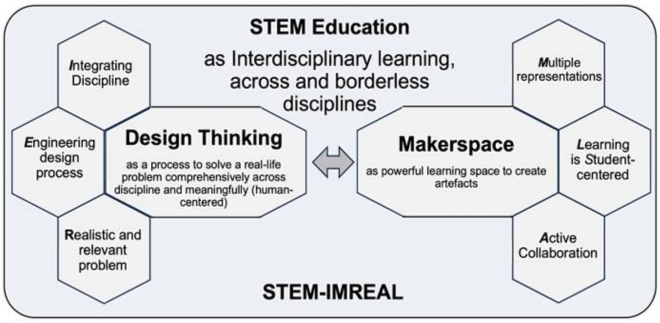

Figure 3. STEM-IMREAL with design thinking and makerspace activity (Source: Authors' own elaboration)

products based on customer needs. It has since been adopted in education to solve complex problems (Chiu et al., 2021; Goldman & Zielezinski, 2016; McCurdy et al., 2020; Nichols et al., 2022; Pande & Bharathi, 2020; Scheer et al., 2012). Design thinking has various definitions; no universal definition exists (Ericson, 2022). In education, design thinking is a pedagogical tool that facilitates complex human-centered problem-solving through collaboration activities (Androutsos & Brinia, 2019; Brady & Katre, 2021; Goldman & Zielezinski, 2016; Nichols et al., 2022). The human-centered approach is an essential characteristic of design thinking, emphasizing real-world community contexts. The learning process involves empathy, and the solutions are based on actual needs (Goldman & Zielezinski, 2016; McCurdy et al., 2020), leading to innovative solutions through an iterative problem-solving process (Androutsos & Brinia, 2019; Brady & Katre, 2021; Chiu et al., 2021; Dorland, 2022; Goldman & Zielezinski, 2016) to solve complex problems that require knowledge and skills from multiple disciplines (Nichols et al., 2022).

The Stanford design thinking model is broadly adopted in educational contexts, e.g., in teacher professional development (Goldman & Zielezinski, 2016), teacher educator program (Henriksen et al., 2017) and student learning process (Simeon et al., 2020). The model has five iterative stages: *empathy*, *define*, *ideate*, *prototype*, and *test*. In design thinking, divergent and convergent practices encourage students to think and explore information broadly and narrowly to solve the problem (Dorland, 2022; Ericson, 2022). The process is similar to EDP, involving a systematic, orderly, and open-ended process of creating and evaluating several possible solutions and optimizing the solution.

Makerspaces

Makerspaces occur across educational settings. For instance, in museum settings through STEM-rich tinkering programs (Bevan et al., 2015), in public libraries through workshops, design studios and group space meetings (Willett, 2016), and in educational institutes. Blackley et al. (2018) and Falloon et al. (2020) used makerspaces in junior schools, Barton et al. (2017) in middle schools with underrepresented youth, Forest et al. (2014) in engineering undergraduate students, and Shively et al. (2021) and Halliburton et al. (2024) with teacher candidates (PSTs). Makerspaces enable participants to create artefacts using physical and digital technologies/materials (Nohra, 2020; Sheridan et al., 2014) that are meaningful and unique (Sheffield et al., 2017). Makerspaces are conducted as collaborative works (Sharma, 2021) that involve participants from all ages, skill levels and across disciplines to create artefacts in creative ways that solve interdisciplinary problems (Sheffield et al., 2017; Sheridan et al., 2014; Shively et al., 2021). Cohen et al. (2017) introduced *makification* as a form of makerspace with four activities as a framework: creation (construction), iteration (development and refinement), sharing (collaborative learning) and autonomy (self-directed activity). Students learn through collaborative, hands-on activities using various representations (e.g., written reports, symbols, diagrams, concrete models, experience-based metaphors, and spoken language).

The space and tools makerspaces depend on the activity's purposes/goals. The learning space is permanent or temporary–a studio (Forest et al., 2014; Sheridan et al., 2014), a laboratory/workshop space (Nohra, 2020), and a classroom (Blackley et al., 2018). Similarly, the tools could be high-tech equipment (such as 3D printers, sewing machines, laser cutters and microcontrollers), traditional craft tools, or everyday resources, both digital and physical (Cohen et al., 2017; Nohra, 2020; Schwartz, 2019; Sharma, 2021; Sheridan et al., 2014). Tools are essential in shaping the spirit of makerspace activities by providing opportunities for exploration and making activities (Schwartz, 2019). Thus, the selection of space and tools is crucial in the makerspace.

STEM-DTaM as an interdisciplinary learning model: A conceptual framework

Drawing on our mapping of the STEM Education literature internationally and from Indonesia (see Nugraha et al., 2023) and the notions developed in this paper, we propose a conceptual framework that integrates the IMREAL foundational components of **STEM** education with **D**esign **T**hinking **a**nd **M**akerspace activities (STEM-DTaM). The STEM-DTaM learning process follows interdisciplinary learning - exploring disciplinary perspectives and then integrating the insights to obtain an interdisciplinary understanding to solve the problem.

The learning steps of STEM-DTaM follow the Stanford design thinking model with two additional actions. First, the real-life issue provokes the students' awareness of the problem and encourages them to participate in the discussion, thus developing the progression to the empathy step. Second, we add reflection and refinement in the last stages in response to the research informing us that the test stage is conducted

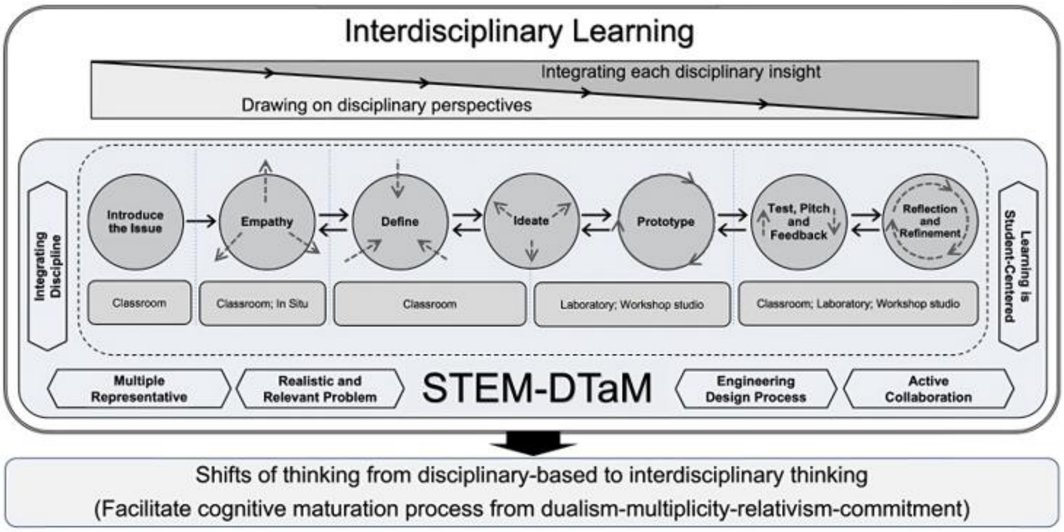

Figure 4. Conceptual frameworks of STEM-DTaM as an interdisciplinary learning model (Source: Authors' own elaboration)

to gather feedback for the improvement of the solution (Chiu et al., 2021; Goldman & Zielezinski, 2016; Henriksen et al., 2017); thus, the students will have more opportunity to learn from the feedback and to obtain a better solution. Hence, we propose STEM-DTaM learning through seven steps: *introduce the issues, empathy, define, ideate, prototype, test and feedback, and reflection and refining*, conducted in different makerspace settings, as shown in **Figure 4**. The makerspace setting is determined based on the purpose of the learning stage. In what follows, the STEM-DTaM learning process is explained.

1. Introduce the issue: The learning process begins with team-building activities and introducing the issue as a learning context to encourage student attention and increase awareness of the problem. Teachers facilitate team-building activities to create a community of learners through a simple challenge. Teams involve students from different disciplinary backgrounds to create an interdisciplinary team where students explore diverse techniques and disciplinary perspectives that lead to innovation (Goldman & Zielezinski, 2016). However, although not ideal, teamwork within the same disciplinary background is acceptable since each person has a unique way of thinking and point of view of the world. We all have a personally formed version of reality, constructed through interaction with each other and the environment that leads to different meanings (Creswell, 2009; Creswell & Creswell, 2017; Kim, 2001).

   The issue constitutes a real-life community and interdisciplinary problem. As aforementioned, the issue should represent a realistic and relevant problem or challenge that students may encounter in their lives (Glancy & Moore, 2013) so that the students find the relevance and value of STEM learning for their future endeavors (Vasquez et al., 2013). Furthermore, the issue represents the integration of STEM disciplines, allowing students to acquire diverse knowledge and perspectives from various fields.

   Introducing the issue is a critical part of constructing interdisciplinary thinking. Students recognize real-life problems are not isolated disciplines; real life is interconnected (English, 2016; Glancy & Moore, 2013; Herschbach, 2011; Shahali et al., 2016). Students realize that multiple disciplines are involved in addressing issues comprehensively. In this sense, the student will face a condition that Perry mentions as the transition from dualism -seeing a single truth- to multiplicity -seeing multiple truths from other perspectives (Golding, 2009; Hursh et al., 1983; Perry, 1981). This cognitive development process represents how students address new information/ knowledge/ or perspective during interdisciplinary thinking.

2. Empathy: Students need to cultivate an understanding of another person's needs and problems. In contrast to the preceding stage, where students discussed the interdisciplinary real-life issue, empathy focuses on people's needs and problems related to the given issue. For instance, in the context of polluted water, the emphasis is placed on the human needs related to water and the challenges to filling the needs. Student empathy leads to learning motivation as the issue and solution respond to actual needs (Goldman & Zielezinski, 2016; McCurdy et al., 2020).

   Empathy is essential in interdisciplinary learning and thinking, allowing students to gain broader insight. In alignment with the interdisciplinary learning characteristic of Newell (2007), empathy facilitates students' gathering of disciplinary knowledge, mainly focusing on people's needs and problems. Disciplinary insight relates to the problem and identifies the connections. This process reinforces that multiple truths exist from various perspectives, as emphasized by Peery's notion of multiplicity (Golding, 2009; Hursh et al., 1983; Perry, 1981). In our polluted water example, students identify diverse insights, concepts, and perspectives from the sciences and technology, engineering, policy, social sciences, and economics.

3. Define: The define stage encourages students to determine the main problem based on the collected information from the empathy stage. In the process, students investigate, criticize, evaluate, and identify the links and conflicts within the information, then integrate them to comprehensively define the needs and problems related to the given issue. This stage exhibits a clear transition from disciplinary to interdisciplinary perspectives, aligning with Newell (2007), who mentions that it involves drawing on disciplinary insights and integrating each perspective to achieve an interdisciplinary understanding. We recommend that teachers facilitate group discussions in the classroom to discuss all relevant information and define the problem. This learning process provides a rich learning experience for understanding the issue (Glancy & Moore, 2013).

Defining the problem is crucial in formulating and generating appropriate solutions and constructing an interdisciplinary thinking process. Jolly (2017) and (English, 2016) highlight that defining the problem constitutes the initial stage in the EDP, which guides activities in addressing the problem and generating solutions. Additionally, the define stage provides an essential cognitive operation in constructing interdisciplinary thinking and integrating or synthesizing knowledge. The term integration in interdisciplinarity refers to the combining of many items, events, or processes to fit them together in such a way as to understand the constituent pieces and the emergent whole better (Clark & Wallace, 2015). In integrating various knowledge and perspectives, students are encouraged to broaden their thinking, find the interconnectedness and commonalities of the knowledge, connect the shattered information, and evaluate methods and assumptions from various perspectives in producing innovative and creative solutions (Vasquez et al., 2013) and constructing their interdisciplinary thinking (Hursh et al., 1983). In this process, students experience what Perry refers to as the transition phase from multiplicity -seeing multiple truths from other perspectives- to relativism -acquiring the ability to consider various perspectives for specific purposes- (Golding, 2009; Hursh et al., 1983; Perry, 1981). Students know that there are many perspectives to understanding a problem, and they consider these perspectives to define the main problem.

4. Ideate: The ideate stage determines the most comprehensive and viable solution to the main problem. In the process, students engage in two main activities. First, they gather all relevant knowledge across disciplines from various resources to solve the problem, such as theoretical support, tools, design, materials and diagrams. Second, they integrate this relevant knowledge to propose various possible solutions, discuss the options, and determine the best possible solution. Given that the problem pertains to a real-life community issue, the proposed solution should be sufficiently evident to be implemented and adjusted to address problems to meet the needs. Conducting this stage in a workshop, studio or laboratory (depending on the problem) informs students of problem-solving spaces, tools, and materials. The tools offer diverse exploration opportunities to create solutions (Schwartz, 2019). Hence, knowing the available facilities could lead students to formulate the most visible solution to addressing the problem. In this stage, students learn from multiple representations, not merely in a traditional written report, but transform it into symbols, diagrams and flow charts, which lead to a high level of conceptual understanding (Glancy & Moore, 2013).

The ideate stage is essential to reinforce interdisciplinary thinking and cognitive maturation development. This stage builds on the experiences of the two preceding phases: encouraging students to collect all relevant information (empathy stage) and integrating them to gain a comprehensive understanding (define stage). The difference is the ideate stage focuses on proposing the solution to the main problem rather than determining the problem. Hence, students experience the iterative cognitive process in constructing interdisciplinary thinking, commencing with disciplinary perspectives and subsequently integrating them to attain an interdisciplinary understanding (Newell, 2007). Furthermore, as students are required to choose their best possible solution supported by appropriate theories, diagrams, flowcharts, and designs, they experience what Perry identifies as commitment, the ability to make an affirmation, choice, or decision based on various perspectives and considerations (Golding, 2009; Hursh et al., 1983; Perry, 1981). Students make a choice and act based on their selection; in this instance, they propose a solution and create diagrams, flowcharts, and designs to elucidate and represent their decision.

5. Prototype: The prototype stage transforms the proposed solution into a tangible, semi-functional, and testable model. In the process, students are encouraged to create a prototype of their suggested

solution using tools, materials, and designs planned in the previous phase. This stage is central to makerspace activity, where students actively engage in hands-on activities to create artefacts using physical and or digital technologies or materials (Nohra, 2020; Sheridan et al., 2014) that are meaningful and unique for them (Sheffield et al., 2017). This learning experience offers the student more opportunity to actively construct their knowledge through what Papert and Harel (1991) mention as learning by making and learning in authentic scenarios through an integrated and interdisciplinary approach. Given that the prototype (or planning diagrams) must be semi-operational and address actual community issues, feedback encourages students to evaluate and enhance their prototypes. Students learn from their failures (Goldman & Zielezinski, 2016), and Jolly (2017) recommends failure as a natural part of the design process and a crucial step toward a solution. This stage provides the opportunity to incorporate all modes of representation (Glancy and Moore (2013), including written reports, symbols, diagrams or pictures (utilized in the worksheet), concrete models, experience-based metaphors, and spoken language (employed in the prototyping process).

Aligned with characteristics of interdisciplinary learning by Newell (2007), this stage represents a culmination in STEM knowledge construction encompassing the development of a new conceptualization (interdisciplinary understanding), creating a model, and testing the model/understanding for problem-solving. In this context, within the framework of the cognitive maturation process by Perry (1981), students are solidifying their commitment as they articulate, elucidate, and present their interdisciplinary understanding in the form of their prototype.

6. Test, pitch, and feedback: This stage collects feedback regarding the prototype to provide information on how closely the prototype meets the people’s needs, identify improvement areas (Pande & Bharathi, 2020), and understand how to create the final product (Goldman & Zielezinski, 2016). The students learn what works and does not, which could lead to necessary modification (Simeon et al., 2020). Students present and demonstrate their prototypes to the teachers, who offer feedback on disciplinary insight, concepts, theory, diagrams, design, and material. This stage also represents an integral part of the EDP, which is communicating the proposed solution to obtain constructive feedback (Jolly, 2017) and provide vast opportunities for students to transform their understanding in what Glancy and Moore (2013) mention as spoken language as one of learning representation form.

7. Reflection and refinement: This stage refines the prototype as a response to feedback from the preceding stages. Students are encouraged to evaluate their ideas and prototypes and consider the feedback a substantive reflection for refining their prototypes. This learning stage provides a robust experience, allowing students to iterate through the learning phases from ideation to the prototyping process and potentially from problem definition if feedback indicates a misalignment with the authentic people’s needs and problems. Hence, this stage offers students opportunities to actively integrate disciplinary ideas, learn in multiple representative forms and employ the entire EDP.

The stage of reflection and refinement assumes a critical role in advancing interdisciplinary thinking and understanding. Within this context, students re-experience the cognitive processes of constructing their interdisciplinary understanding according to Newell (2007), including gathering relevant disciplinary knowledge (from the feedback), identifying the connection, resolving conflicts, constructing a better interdisciplinary understanding, then producing and testing an improved model to solving the problem. This process gives students a more profound and accurate interdisciplinary understanding of the issue. In the context of the cognitive maturation process by Perry (1981), this learning stage facilitates a transition for students from a state of multiplicity to relativism and finally to a state of better commitment, where students make decisions and propose an enhanced idea and prototype based on a thorough consideration of various perspectives.

CONCLUSION

Interdisciplinary thinking is an essential thinking skill and dedicated interdisciplinary learning is required to facilitate the construction of this thinking. STEM education has the potential to facilitate this process. Our research-informed STEM-IMREAL framework of foundational components provides STEM educators with the essence of STEM learning. We have further integrated the research literature to guide the implementation of interdisciplinary knowledge formation by considering design thinking and makerspaces. This has created the STEM-DTaM (STEM with **D**esign **T**hinking **a**nd **M**akerspace) learning model that transforms the foundational concepts of STEM-IMREAL into a practical learning process. The learning process is a modification of the Stanford design thinking model. STEM-DTaM introduces the issue to stimulate students’ awareness of an interdisciplinary real-life problem and concludes with reflection and refinement, aiming to attain an enhanced solution.

The STEM-DTaM learning model offers an interdisciplinary learning experience aimed at helping teachers and students construct interdisciplinary thinking. The process provides students with rich and iterative interdisciplinary learning, initiated by gathering and understanding various disciplinary perspectives and then integrating these perspectives to obtain an interdisciplinary view as a comprehensive understanding and solution to solve the problem. The learning process facilitates cognitive maturation theories, as Perry (1981) described, that explain how students develop their interdisciplinary thinking. The process assists students in shifting their intellectual stage from "*dualism*" (see a single truth: right-wrong, true-false) to "*multiplicity*" (see multiple truths from other perspectives) to "*relativism*" (acquired the ability to consider various perspectives for specific purposes), then to "*commitment*" (ability to make an affirmation, choice, or decision based on various perspectives consideration) (Golding, 2009; Hursh et al., 1983; Perry, 1981).

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