Transdisciplinary Role of Technology in STEM Education

Çağlar Naci HIDIROĞLU[1], Aytaç KARAKAŞ[2]

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[1] caglarr.naci@gmail.com
Pamukkale University-Department of Mathematics Education
ORCID: 0000-0002-3774-4957

[2] aytackarakas@gmail.com
Pamukkale University-Department of Science Education
ORCID: 0000-0003-2088-1522

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ABSTRACT

Today, the integrative STEM initiative, which is at the center of the current paradigm shift in education, includes attempts to blend science, mathematics and engineering with technology education. Common considerations provide an opportunity to better define the role of technology within the framework of STEM education, but this has not yet been fully realized. Therefore, a lack of definition/role of technology in STEM education is quite noticeable and there exist different perspectives regarding this issue. This theoretical study explains the basic principles regarding the transdisciplinary role of the technology that is defined with certain limits, while discussing different ideas about the integration of science and technology in STEM education in the last 30 years in order to present a different perspective on the role of technology in STEM education.

Keywords: *STEM education, technology integration, transdisciplinary approach.*

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INTRODUCTION

Humanity has encountered many paradigm shifts [*scientific revolutions as Kuhn (1962) puts it*], from hunting to agriculture, from agriculture to industry, and then to the information age. In this information-based society that we live in, the rate of the changes in technology occur in an incredible extent. This indicates that the integration of technology into the 21st century education must be transformed in such a way that ensures catching up with the science and technology of the current age, and active participation of schools in this transformation is indispensable. Although technology is not a new phenomenon in the broad field of education, research on educational technology is packed with conceptually irrelevant, meaningless or inconsistent thoughts, and many concepts related to technology are applied incorrectly, incompletely and ineffectively in the classroom environment, and are trivialized (Bull et al., 2019). According to the study conducted by the The Organisation for Economic Co-operation and Development [OECD], in which adult skills were examined, the problem-solving skill level in technology-rich environments, especially in the 20- to 30-year-old age group, was quite low considering both the OECD average (*approximately 8%)* and the average of Turkey (*approximately 2%*). This is a noteworthy indicator revealing the failure in raising individuals who can use technology effectively.

Today, the transdisciplinary STEM initiative, which is at the centre of the current paradigm shift in education, intends to blend science, mathematics, and engineering with technology education (Sanders, 2009). However, most educators are not prepared enough to master sufficient content knowledge of science, technology, engineering and mathematics or pedagogical content knowledge to teach more than one subject area at the same time (O'Neal et al., 2017; Warner, 2003; White, 2014: Zubrowski, 2002). Technology and engineering are the least represented and funded fields in STEM education, especially in K-12 education (Miaoulis, 2009). Technology and engineering in STEM education in K-12 seem to be a stumbling block to producing a meaningful STEM learning experience for students. When the literature is examined, it is possible to mention several possible reasons for this (White, 2014):

- STEM is a specifically recognized and embraced approach in mathematics and especially in science education. Most educators in these fields feel comfortable while teaching STEM content appropriate to their field. Therefore, educational silos are formed.
- STEM educators who are not closely related to the engineering or technology field worry about these processes.
- STEM proprietors in education are particularly unsure of what exactly engineers do in terms of education.
- STEM educators treat technology mainly by considering the role of computers.

The lack of the definition/role of what is denoted with T in STEM education is obvious and most researchers have ignored this problem (Herschbach, 2011). The passive role of technology in STEM education results from lack of access to resources, technical problems, and teachers' resistance to change and their negative attitudes (Jones, 2004). Ertmer et al. (2012) mentioned about external and internal obstacles in technology integration, and underlined teachers' attitudes, beliefs, and knowledge as the most important internal obstacles. Both teachers and students use technology primarily as consumers of exploitative knowledge and, to a lesser extent, as knowledge producers. The meaningful and effective use of technology with the aim of ensuring learning and raising designer students who can shape the future depends on the teacher. It can be argued that teachers generally use technology according to their own skills and the needs of their students (Ottenbreit-Leftwich et al., 2010). Since science and mathematics teachers lack the engineering knowledge and skills to integrate engineering into their curriculums, technology teachers are often asked to introduce engineering concepts into K-12 education (Sanders, 2009). Ring-Whalen et al. (2018) and Dare et al. (2019) determined that teachers have difficulty in verbally describing what technology means in the context of STEM education, and sometimes they refer to technology as the "mysterious part". Even though teachers are aware of the value of technology in the teaching and learning process, they need more guidance on what 21st century skills are and how technology should be integrated effectively (O'Neal et al., 2017).

Considering the context of STEM, in the beginning, high-quality STEM curriculum and professional development opportunities were rare. The rise of STEM education has provided an opportunity for the education community to better define the role of technology in the STEM education framework, but this has not yet been fully realized. Innovative Teaching and Learning Research Project, which revealed teachers' views on the use of information and communication technologies [ICT] in seven countries, showed that technology is still used in basic ways as required by traditional teaching, rather than developing collaboration and knowledge (Fullan & Langworthy, 2014). Similarly, Wang et al. (2011), in the study in which they investigated the perceptions and practices of teachers regarding technology in the STEM-supported learning process, concluded that teachers had the most difficulty in understanding the role of technology and how to integrate it. The most outstanding questions today about the technology integration in education are as follows: How technology can help deepen STEM education and develop students' 21st century skills; how it can support thinking, creativity, student participation and teamwork; how it can make STEM teaching and learning more effective, appropriate, accessible and individual, and how large numbers of students can be effectively educated with technology within STEM context (Lakshminarayanan & McBride, 2015).

While different perspectives and definitions in STEM education increase complexity, it can be noted that scientists meet on a common ground in terms of basic issues. Integrated STEM teaching (a) uses real-world contexts to engage students in authentic and meaningful learning (Bryan et al., 2015; Burrows et al., 2017; Kelley & Knowles, 2016; Sanders, 2009), (b) uses student-centred pedagogies, including inquiry-based learning and design thinking (Bryan et al., 2015; Kelley & Knowles, 2016), (c) supports the development of 21st century competencies such as creativity, collaboration, communication and critical thinking (Bryan et al., 2015; Honey et al., 2014) and (d) enables students to clearly establish connections between STEM disciplines (Bryan et al., 2015; Burrows et al., 2017; English, 2016; Herschbach, 2011; Honey et al., 2014; Kelley & Knowles, 2016). Aside from common considerations, STEM educators still do not have a clear understanding of the role technology plays in STEM education initiatives. In addition, it is aimed to create effective learning environments by combining the discussed context with the components of STEM homogeneously. For this reason, it is necessary to determine the roles of technology in STEM, to be cognizant of the relations between the disciplines and to understand the homogeneous structure in which the disciplines meet.

Science is one of the concepts that is most likely to be confused with technology. One of the reasons for this is that they cannot be recognized as two different components of a process, since they are complementary concepts (Brooks, 1994). The main distinguishing feature between science and technology stems from their purposes. The purpose of science is to understand the natural world. On the other hand, the purpose of technology is to make changes in the world to meet human needs. The necessary information to develop a new technology comes from the scientific information obtained as a result of scientific research. Technology doesn't have to come after science, though. Sometimes technology can get ahead of science. For instance, the desire of humans to fly like a bird, the need to quickly reach from one place to another or to carry loads has led to the invention of many flying vehicles. Although these flying vehicles, which were invented without the necessary scientific knowledge, have many insufficient / missing features, they are all examples of technology and can satisfy the needs to a certain extent. Technology directs the development of science and scientific developments provide an opportunity for more advanced aircraft technology. A real-life problem often has both scientific and technological aspects. The need to seek answers to the problems in natural life leads the development of technological products while, at the same time, technological needs can also guide scientific research. Technological inventions, from pens to computers, are important technological tools that enable us to understand problems in real life (National Research Council [NRC], 1996).

Technology is also confused with engineering. Engineering refers to science-based research and development to create specific designs while solving problems in real life. Engineering produces technologies to solve problems, but this does not mean that engineering produces all the necessary technology. Someone with insufficient science or engineering knowledge can find new ways to make a machine work faster. This is an example for technology. Science and engineering, on the other hand, can explain the excellent functioning and working principle of this invention later. At a later stage, new technologies developed through engineering may also yield new opportunities. Man's constant desire to achieve the better shapes the history of humanity together with the use of technology, engineering and science.

The importance of STEM in the 21st century education encourages researchers to seek a comprehensive answer to the question of how we should integrate it into schools. There are several ways to integrate STEM into schools. One way is to teach each discipline as a separate school subject with some or no integration. The second way is to teach each of the four subjects separately, while also choosing one or two of the components for in-depth learning. The third way is to integrate one of the STEM disciplines with the other three disciplines; for example, the content of technology can be integrated into science, engineering and mathematics courses (T-S, E, M). The fourth way is to integrate all four subjects more comprehensively into a single school subject (Dugger, 2010). Different perspectives on the integration of technology into education, which is an important discipline of STEM, will give us important clues about how we can use technology in integrated and transdisciplinary STEM learning processes at advanced levels.

An overemphasis in the curriculums on educating knowledge workers in mathematics and science fields may understate the opportunity for students to be knowledge producers and to produce technological designs with real tools and materials. However, students who develop techniques with only technology-oriented skills are not aware of the mathematical and scientific knowledge underlying their work or do not value them. STEM education should help technology-oriented students better understand these fundamental subjects/disciplines. Engineering builds a bridge between systematic planning and fundamental knowledge and technological development through design. Raizen et al. (1995) described the cycle of technology use in the classroom in nine steps as: (1) analysis & research, (2) structuring the design brief, (3) gathering information, (4) generating alternative solutions, (5) choosing the best solution, (6) improving the solution, (7) prototyping, (8) testing and evaluation, (9) redesigning and re-implementation. Understanding the role played by technology and engineering in the broad spectrum of the STEM movement may not be easy for many STEM educators. Technology and engineering are the agents that help bring science and mathematics to life through application. All STEM disciplines are interconnected like threads on a steel cable (Snyder, 2018).

METHOD

This research is a theoretical review study. Review studies include revealing common trends and deficiencies by comprehensively examining all important studies within the scope of research, synthesizing these studies in the context of the research topic, and presenting a new theoretical or intellectual perspective for future studies (Oakley, 2012; Petticrew & Roberts, 2006; Torgerson, 2003). Thanks to theoretical review studies, scientific gaps and original applications in the literature for a current research topic are determined (Gough et al., 2012; Petticrew & Roberts, 2006; Polanin et al., 2017).

In this direction, in this study, general tendencies and deficiencies in studies on STEM integration in education have been revealed, and a theoretical framework that will offer a current and different perspective by synthesizing the approaches that will serve the expected STEM integration in the future is presented.

The Transdisciplinary Role of Technology

Honey et al. (2014) mentioned three different perspectives on technology integration in STEM. First, technology in STEM education can be viewed as a product of engineering considering its historical link with vocational education. Secondly, technology can be defined as educational/instructional technology used to improve teaching and learning. Finally, technology can be defined as tools used by science, mathematics and engineering practitioners. Of the three perspectives proposed by Sivaraj et al. (2019) regarding the role of technology in STEM education, two perspectives overlap with those of Honey et al. (2014), namely the engineering product and educational/instructional technology product. However, Sivaraj et al. (2019) expressed the third and the other role of technology in STEM education as coding or computational thinking, which can complement mathematical and engineering thinking in various contexts. Four perspectives presented by Ellis et al. (2020) [including (a) vocational education, industrial arts or engineering product, (b) education or training technology, (c) computation and computational thinking and (d) tools and applications used by practitioners of science, mathematics, and engineering] take us one step further in these classifications, and the fourth perspective, in particular, leads us to a new perspective that cannot be ignored. On the other hand, although the fourth perspective offers a philosophical stance in explaining the role of technology, this perspective needs to be explained in detail. Offering a transdisciplinary role to technology integration, this perspective is in many ways compatible with the other three perspectives. Here in this perspective, the engineering role, instructional role and computational/robotics role of the technology have an important place; however, it remains insufficient to explain the role of technology in the learning process. The transdisciplinary role of technology means much more than the combination of these parts, and the blended structure offers a homogeneity and so a stronger structure than the combination of the parts. The primary source of technology in its transdisciplinary STEM role is context and interconnectedness that makes context meaningful. In transdisciplinary STEM, scientific inquiry, engineering design, mathematical modelling and computational thinking are the four basic skills in maintaining homogeneity and interconnectedness of the dimensions. Technology acts as an instrument in the establishment of the homogeneous structure, which is appreciated in transdisciplinary understanding, and plays a role in establishing connections between disciplines and providing interconnected wholeness. Technology should be seen as an essential mental semiotic mediator in explaining the chaotic structure of real life in its natural state. Interconnectedness should be established by giving importance to the historical or intellectual development and interaction of the context. This interconnectedness should be natural, but not artificial. The structure of the contexts should be handled with their naturalness in real life. Over the past 50 years, numerous researchers have offered different perspectives on the essence of technology's role in education. By making a comprehensive synthesis considering these studies, the true nature of STEM in the 21st century can be better understood as well as the importance of integrating technology into STEM education (Snyder, 2018).

This theoretical study discusses various ideas about technology integration in science and STEM education in the last 30 years in order to present a different perspective on the role of technology in STEM education and explains the basic principles of the transdisciplinary role of technology with certain limits. Within the scope of the study, the theoretical model describing the transdisciplinary role of technology in education is basically predicated on the latest approach in the nine STEM approaches explained by Bybee (2013) without specifying level and the last of the four integration levels of Vasquez et al. (2013) (*Level 4: Transdisciplinary STEM*) and the model provides a comprehensive theoretical framework (see Figure 1).

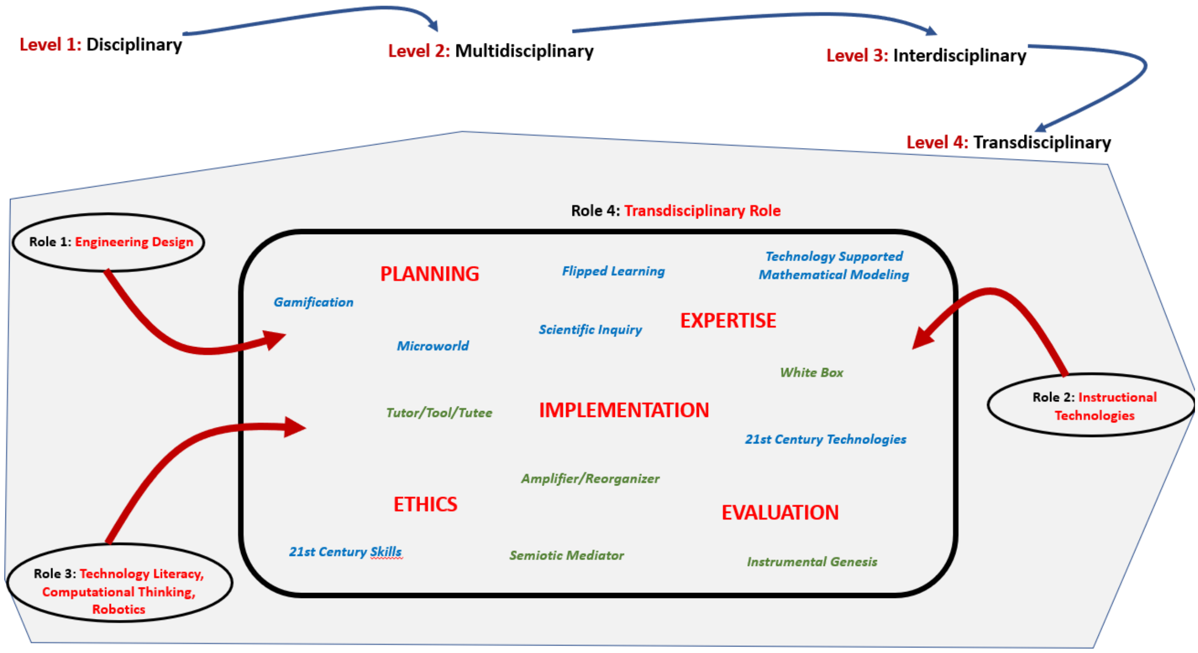

Figure 1. *The Transdisciplinary Role of Technology in STEM Education*

The five basic dimensions in the transdisciplinary role of technology are of critical importance in ensuring the interconnectedness between different approaches, theories, strategies, methods and techniques. While three of these dimensions including *planning/designing teaching*, *implementation/executing the teaching process and evaluation* are procedural dimensions, the other two including *ethics and expertise* are situational dimensions. In the process of planning/designing teaching, the following are essential in revealing the transdisciplinary role of technology: determining the roles of technology, determining technology-supported learning strategies/methods/techniques, considering open-ended interdisciplinary real-life problems of the age that will reveal 21st century skills, creating a digital resource pool for students, preparing a technology-based physical environment, providing peer support/cooperation, making plans in which new technologies can meet students' individual differences, employing technology that calls for collaboration (such as *paired programming*), taking students' technology background and skills into account, developing holistic/analytical rubrics, and considering the possible diversity in the use of technology and being aware of these. During the process of *implementation/executing teaching,* aspects such as maintaining a harmony between technology and mind, producing effective solutions against technology-based unexpected events, applying the plan and changing it effectively when necessary, providing effective guidance considering students' thoughts and giving appropriate feedback serve for the transdisciplinary nature of technology. In order to reveal the transdisciplinary role of technology, in the evaluation process, it is essential to conduct an evaluation that takes the transdisciplinary role of technology into account in the evaluation process, to use evaluation tools such as digital portfolios, holistic/analytical rubrics effectively, to apply different evaluation methods (*such as in-group, intergroup, self-assessment),* to provide opportunities that allow for better designs and to give appropriate feedback. In the transdisciplinary role, the ethics dimension attaches importance to being aware of the ethical use of resources in digital environments, acting in accordance with the principle of equity, being an effective guide in accessing the right resources and information, paying attention to professional ethics and scientific ethics. The dimension of expertise in the transdisciplinary role includes being able to follow the innovations related to technology integration in one's field, leading innovatively, and effectively integrating new technology in different fields into his/her own field. These dimensions serve as a skeletal system in forming the transdisciplinary nature of technology. Within the scope of the study, the principles on which the transdisciplinary role of technology is based are as follows:

(1) The engineering role of technology, its role of instructional technology, and the role of technology literacy-computational-robotics have an important place in the transdisciplinary role of technology; however, these three roles are insufficient to explain the transdisciplinary role of technology in the learning process. The blended structure formed by the transdisciplinary role offers a stronger structure than the combination of these parts.

There exist several possible answers to the question of what the desired student outcomes related to technology in STEM teaching would be. Besides, one of the most important outcomes of this question is innovation, which is directly related to the definition of technology. Looking at history in terms of technological developments, there has been a technological innovation behind every event causing paradigm shift. The discovery of America is based on the invention of sailing ships that can travel for long periods of time. The issue of dissemination of ideas was related to the invention of the printing press and hence the increase in the number and availability of books. Manufacturers are expected to engage in an iterative engineering design process to create these products (Rodriguez et al., 2018), which makes this use of technology the most important example of technology as an engineering product. Within the framework of K-12 science education (NRC, 2012) and in next-generation science standards (NGSS Lead States, 2013), technology is clearly defined as an engineering product. According to this understanding, technology emerges as a result of the actions taken by engineers to design ways to meet human needs and desires by reflecting their understanding of natural world and human behaviour (NRC, 2012).

Given that the primary use of technology in classrooms in America still includes computer-based practice and application, business applications, and information access via the web, the continuing perception of the T's instructional technology role is not surprising (Anderson & Ronnkvist, 1999). According to Afterschool Alliance (2008), technology allows students to apply what they have learned through computer-aided designs and animations and to explore concepts in a more detailed and practical way. Seels and Richey (1994) described instructional technology as the design, development, use, management and evaluation of the processes and resources for learning.

Performing numerical analyses according to theoretical knowledge in the fields of science has made it possible to solve complex problems that could not be solved for many years with simulation and statistical calculations. This understanding specifically deals with complex problems that include more than one solution to current open-ended real-life problems. When the studies based on technology and computational thinking in mathematics education are examined, it is seen that there has been an increasing trend in focusing on their relationship in the last 10 years. The fact that these studies are independent of STEM and mathematical modelling can be seen as a limitation, and the transdisciplinary role of technology aims to include it in this process and thus to eliminate this limitation.

This is where one of the misunderstandings arises when considering the "T" in STEM. Many people believe that technology integration in STEM simply refers to the application of computers and/or instructional technology devices and software. Although computers are a vital part of the equation in technology integration, they are only one of many technological tools (White, 2014). Technology educators demand an extra emphasis particularly on the engineering role of technology. With an interconnected holistic understanding, the transdisciplinary role of technology encompasses these parts and opens its doors to a wider world. In this way, while including the deficiencies of these parts in the process, it also reveals the relationships between the parts, and provides the opportunity to reach the whole, which is more than the combination of the parts, by establishing a homogeneous structure. For example, Galileo's showing the moons of Jupiter through his telescope did not only enable humanity to discover these moons but also proved the idea proposed by Copernicus a century ago indicating that the Sun does not revolve around the Earth, but that the Earth revolves around the Sun. As a result, this led to the acceleration of the Reformation and Renaissance process. Interconnected wholeness is a concept that was introduced in studies in neuroscience that gained acceleration after 2012 and will lead to a paradigm shift in our scientific method, especially with the recognition and development of new mathematics that it needs it (Kılıç, 2021). It is such a concept that refers to a new system of thought and a life modelling; that is, a new mind structure that has the potential to affect culture and change our perspective not only in science, but also in many fields of life from economics to education, law to health, nature to life. As an example, if we approach computational thinking with this interconnected wholeness approach, big data gives us the opportunity to derive meaning from this data and to make associations with it by considering different technology uses, rather than collecting so much data with technology (Bundy, 2007; Helvacı et al., 2021). This approach enables us to both consider the roles with a deeper understanding and reveal the transdisciplinary role with an interconnected wholeness by highlighting the relationships between the roles.

(2) In the transdisciplinary role of technology, gaining and developing the ability to use the technological tools and equipment used by real-life engineers and scientists come to the fore. Teachers should develop solutions to current problems together with their students (Çorlu, 2021). Technology for All Americans Project (International Technology and Engineering Educators Association [ITEEA], 2011) defines technology as human innovation that can change the world to be able to solve real-life problems and satisfy human needs/wants. In this sense, technology and engineering education is a problem/project-based learning in which students use the principles of mathematics, science, engineering and technology. In this process, it is essential to design, develop and use technological systems, to use open-ended problem-based design activities, to utilize cognitive, guiding and effective learning strategies, to apply technological knowledge and processes to real-world experiences using up-to-date resources, and to work both individually and in a team to solve problems. (ITEEA, 2011). According to Novak and Krajick (2004), using instructional technologies in an inquiry-based classroom allows students to see how scientists work in the real world and lead them to act like scientists. Students can collect and analyse real-time data just as scientists do. Bell & Bull (2008) suggested that technology should be used in a science classroom "to facilitate data collection and analysis, to improve scientific understanding through imagination and visualization, and to expand research through communication and collaboration". Since technology is a central issue, including everything from scales to supercomputers, in the original works of STEM professionals, (Niess, 2005), technology can also be viewed as tools and practices used by science, mathematics, and engineering (Honey et al., 2014). Courses should enable students to experience the existing reality immediately (Çorlu, 2021). To support students' participation in the authentic practices of STEM professionals, learning tasks should cover the use of STEM-specific tools or technologies (Bell & Bull, 2008; Guzey & Roehrig, 2009; McCrory, 2008; Niess, 2005, Novak & Krajick, 2004).

(3) In transdisciplinary STEM, scientific inquiry, engineering design, mathematical modelling and computational thinking skills appear as the four basic skills of the transdisciplinary role, which is important in ensuring homogeneity and interconnectedness of dimensions. These four basic skills are 21st century skills and also serve for interdisciplinary and transdisciplinary understanding and contain components and connections that will bring each discipline to a blended homogeneous structure with interconnected wholeness approach. For instance, while transdisciplinary understanding of STEM includes computational thinking in learning contexts, the focus of computational thinking is not limited to this (*as in the example of learning a new programming language without any context)*. In today's increasingly digitalized world, the transdisciplinary understanding of STEM regards computational thinking as essential in a STEM learning context where other basic skills are exposed. In other words, computational tools and skills in a STEM context create unique opportunities to deal with real-world problems and allow for designing meaningful solutions through coding for real problems in this digital age. Computational thinking evolves into this understanding in the transdisciplinary role of technology. Çorlu et al. (2014) mentioned four teaching methods similar to this approach (see Figure 2). In this theoretical study, unlike Çorlu et al. (2014), these four parts are not seen as a teaching method, but as a basic skill set that supports 21st century skills, and in the engineering part, the concept of engineering design (skill) is included instead of project-based learning methods.

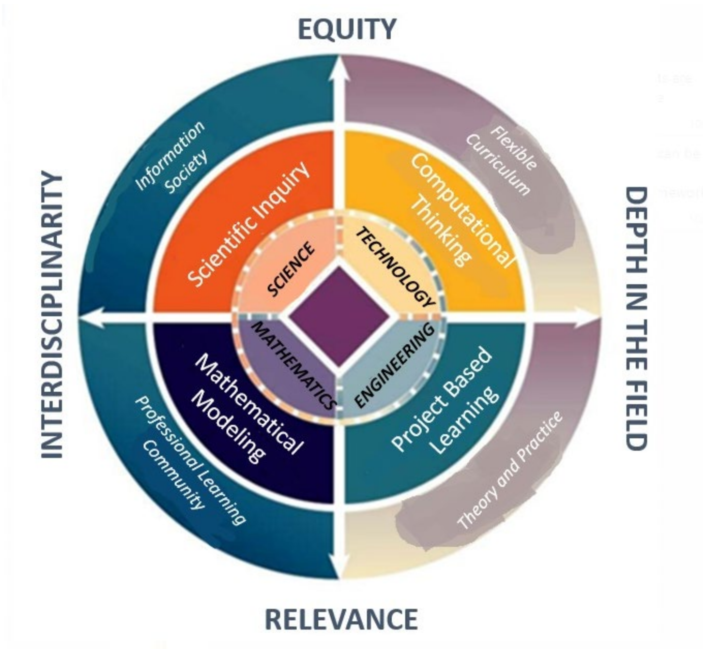

Figure 2. *STEM: Integrated Teaching Framework (Çorlu, 2021).*

These four basic skills, which take part in the transdisciplinary role of technology, are important because of the fact that they are necessary when seeking answers to the current real-life problems of the 21st century and they can be highly linked with each other due to their high interconnectedness. The transdisciplinary role of technology serves for a skill- and creativity-based understanding far beyond disciplinary understanding. It adopts learning environments that consider and reveal 21st century skills. Encouraging students for STEM participation is a necessity not only to prepare students for future STEM careers, but also to equip students with 21st century competencies in general (Honey et al., 2014). While the four key skills in the transdisciplinary role of technology provide a rich process that unearths 21st century skills, current skills need to be followed and consciously included in the process to reveal the transdisciplinary role.

(4) The primary source of technology in the transdisciplinary STEM role is context and interconnectedness that makes the context meaningful. This interconnectedness should be natural, but not artificial. The structure of the contexts should be dealt considering their naturalness in real life. In knowledge-based life, relationships are more important than knowledge itself according to the holistic approach (Çorlu, 2021). Events in real life are chaotic structures that contain a high level of interconnectedness. This interconnectedness is the main reason for the chaotic structure and includes naturalness. The solution of the chaotic system in the content of this naturalness is meaningful, and the greater the interconnectedness is, the greater the complexity becomes. The chaotic structure cannot be easily explained with a specific mathematical model. Although simplifying the solution is a strategy, it is necessary to do it wisely, to try to preserve the naturalness of the chaotic structure in real life, and to minimize the fallacies and limitations that may arise from simplification. It may be possible to explain the chaotic system, where there is a lot of interconnectedness, in a more comprehensive way with an effective combination of technology and the human mind. In the transdisciplinary role of technology, technology plays important and indispensable roles as a homogeneous structure in the mental process in order to derive deep and effective meanings from big data (*this is the real information, not data*) and provides opportunities to accept complexity in all its naturalness.

The first stage of this interconnectedness is the examination of the emerging thought in a cause-effect relationship. Scientific actions develop their methods throughout the history of science (Helvacı et al., 2021), which is made possible through interconnectedness. For example, Aristotle noted 2400 years ago that if you let a 10 kg iron mass and a 1 kg iron mass fall at the same time, the heavier one would fall to the ground faster. This idea has been accepted as correct by humanity for about 2000 years. At the beginning of the 1600s, Galileo went to the tower of Pisa and did his famous experiment; Aristotle was wrong, and the experimentalist approach (induction articulated on deduction) began (Hıdıroğlu, 2018). As a result of the contributions of thousands of important minds and the compilation of their ideas, the information network has been formed. All scientific knowledge is meaningful with the body of relations between each other. None of them means anything on their own and their value is hidden in their existing relationships. Therefore, the whole is much more than the sum of the parts and even different from them (Helvacı et al., 2021). This interconnected wholeness approach is a structure that articulates on induction and deduction. One of the most basic features of STEM activities is to handle scientific/mathematical concepts homogeneously without separating them from each other (Thibaut et al., 2018). While the problems of the future are too complex to be solved by separating the disciplines, a transdisciplinary understanding will allow the emergence or discovery of new structures or discipline-like things (Aslan Tutak, 2020). In an integrated STEM approach, schools do not prepare students for school, schools should be a natural part of life (Çorlu, 2021), and for this, real-life contexts should be handled in their most natural state, not in a discipline-specific way, and should be treated with a transdisciplinary understanding.

(5) Technology acts as an instrument in the establishment of the homogeneous structure that the transdisciplinary understanding considers. This instrument plays a role in establishing connections between dimensions and providing interconnected wholeness. Technology as an important mental semiotic mediator in explaining the chaotic nature of real life in its natural state provides the connection between the mind and the technological world (Balacheff & Kaput, 1996). In order to receive effective and accurate feedback from technology, the relationship between mathematical language and technological language must be established correctly (Nicherson, 1995). For example, getting feedback from a software about drawing a graph without errors or comparing multiple demonstrations helps students develop thinking. With technology, mental (*internal*) representations become external representations (*such as computer models, 3D parts, engineering products*), and learners develop or revise their internal representations with the feedbacks from the technology (Hoyles, 1995). Vérillon and Rabardel (1995) emphasized that technology may correspond to a wide range of different roles in students' minds. In other words, individuals or groups from the same class who solve a given task using the same technological tools can employ various strategies (Artigue 2002; Mariotti 2002). According to the Instrumental Genesis theory, a technological artifact that will be used in teaching turns into a special and different instrument by establishing an effective connection with the mind of the student. In this regard, Drijvers and Gravemeijer (2004) remarked that the uniqueness of each student's mind creates a richness. Instrument is defined as a world or structure created between the individual performing the action and the technology (tool) used in the action (Rabardel, 1995). A technological tool turns into an instrument with the mental development of the individual who will use it. If there is a significant relationship between a user and artefact, then the artifact can become an instrument (Rabardel, 2003). This is achieved through the establishment of the interconnected wholeness between mind and technology. The structure of the instrumental formation depends on the characteristics of the tool (such as computer software) and the characteristics of the individual (knowledge and skills). Therefore, a technological tool is transformed into different instruments by different individuals. Trouche (2004) and Drijvers and Gravemeijer (2006) named user's thoughts (*subject→artefact*) regarding the contribution of technology to self-thought in the process as instrumentation, and user's thoughts (*artefact→subject*) about what s/he can do to use technology effectively as instrumentalization.

Heid (1997) pointed to four basic principles in technology-supported mathematics classrooms: (1) student-centred education, (2) working like a mathematician through technology, (3) technology and reflection, and (4) redefinition of epistemological authority with technology. In other words, in the process of learning mathematics, the learner should use computers actively to learn mathematics and do mathematics, and see computers as a source of authority in learning by revealing high-level skills. Computer software should offer the student the opportunity to act like a mathematician and aim to reveal high-level mathematical skills (Noss, 1998). The features of each software to be used in the mathematical learning process are different from each other. For this reason, it is important that the features of the software are well known and that their contribution to the mathematics learning process is discovered by the teacher and the student.

(6) In the transdisciplinary role of technology, technology is not only seen as an auxiliary tool for learning; there is a conscious integration of technology in this process. Emphasizing the conscious use of technology, Buchberger (1990) elaborated a dichotomy related to technology's roles as black box and white box. In the white box role, the student is aware of the interconnectedness and relationship between technology and mathematical/scientific concept/content. According to Buchberger, technology is being used as a white box when students are aware of the mathematics they want technology to perform; otherwise the technology is being used as a black box. He argued that the use of symbolic manipulation software (i.e., CAS) as a black box can be "disastrous" (p. 13) for students when they are initially learning some new area of mathematics – a usage that is akin to the Tool mode within the Tutor-Tool-Tutee framework. Cedillo & Kieran (2003) noted that the white box-black box approach indicates two extremes, and technology also plays a grey box role for student thinking.

The primary goal for developing an up-to-date approach to STEM education is to consider environments that will develop 21st century skills as well as new skills that support an advanced workforce. (Bybee, 2013). The skills revealed by different frameworks (OECD, 2007; P-21, 2015; ATC21S-EU, 2006) aiming to explain 21st century skills show some differences. Taking the similarities into account in these frameworks, Lee & Tan (2018) explained 21st century skills with a four-dimensional model (thinking, interpersonal, career-life, information-media-technological literacy).

In order to acquire these mentioned skills, EU Key Competences for Lifelong Learning (EU, 2006) highlighted the skill of learning to learning as a prerequisite skill. The transdisciplinary role of technology increases motivation in learning and provides the opportunity for rich mental processes that will support conceptual learning and thinking about what has been learned (metacognition) (Jonassen, Peck, & Wilson, 1999). Technology provides virtual representations of a real situation/event, allowing students to move objects and observe their results (Drijvers & Gravemeijer (2006).This situation also supports technology's scaffolding role, an important concept in Vygotsky's social cultural theory [*scaffolding is the mental-structural support that a person provides to the learner in the learning process in line with the learner's proximal development area (Noss & Hoyles, 1996)].* Computers offer the learner the opportunity to learn information with maximum efficiency through an effective integration.

Taylor put forward an important view of how technology should actually be handled considering the role of computers. Taylor (1980) mentioned three basic roles of computers in education as tutor, tool and tutee. In the role of tutor and tool, students and teachers do not need high-level technology skills, and these two roles cannot contribute to the process for mental development and conceptual learning as in the tutee role of the computer. The transdisciplinary role of technology does not overlook the tutor and tool roles, but overemphasizes the importance of the tutee role. In the transdisciplinary role of technology, technology is not only a tutor or a tool, but especially in the role of tutee, it also supports the rearrangement and enhancements of thoughts in the process. This indicates the effective role that technology can assume. Students and teachers should take a proactive role in the integration of technology into the learning process. In another important point of view, Papert (1980), who led to an important evolution of thought in the integration of technology into education, constructed mathematics learning processes with the LOGO programming language, and mentioned student-centred technology-supported learning environments, which he refers to as the microworld. According to Papert, technology refers to effective tools for doing and exploring mathematics. The transdisciplinary role of technology, in line with the approach of Papert, regards students as designers who try to achieve the better in the process of acquiring knowledge in its natural state in the learning process. By providing open-ended learning environments supported by microworld technology, students are allowed to work on much more complex problems (Papert, 1980). While Brown (1985) defined technology as "idea amplifiers", Pea (1985; 1987) mentioned about the concept of cognitive technology and defined it as technologies that help overcome the limits of the mind in the learning and problem-solving process. The use of technology to visualize geometric shapes and graphics or to obtain views of geometric objects from different directions is an example of cognitive technology. Cognitive technologies play two roles in education, namely as amplifier and reorganizer (Pea, 1985). In the amplifier role of technology, mental strength (*reducing cognitive load*) comes to the fore, while in the reorganizer role, making use of different perspectives and revising (*expanding/correcting*) mental actions are in question. Using a scientific calculator or a digital table for detailed calculations and analyses while solving open-ended real-life problems minimizes operational errors and provides mental empowerment by reducing the mental load in the process by reaching a more accurate and detailed data set quickly. On the other hand, the reorganizer role has the power to influence or change the focus and perspective in students' mathematical thinking (Pea, 1987). Technology can make some aspects of a situation/event in a context visible with new representations and different connections for better understanding and enable students to obtain feedback that they cannot access without technology. With technology, the learner's mental schema develops and his thoughts about the nature of mathematical concepts are rearranged. For example, in the construction of triangle inequality, students' forming different triangles with technology and making sense of the inequality which is abstract with different perspectives are examples of this. In this case, the learner rearranges his knowledge and creates a better mental schema. Hıdıroğlu (2015) argued that in the mathematical modelling process enriched with technology, mathematical analysis draws students’ attention from operational focus to conceptual and relational focus (*amplifier*) and reveals their higher level and richer mental thoughts (*reorganizer*). Although the transdisciplinary role takes these two roles into account, it especially aims to highlight the reorganizer feature.

(7) Some new teaching approaches, strategies, methods or techniques play an important role in the formation of the transdisciplinary role of technology. Just as dimensions are homogeneous in the transdisciplinary structure, new understandings are effective parts of this homogeneous process. The absence of content-oriented technology applications poses a unique challenge for science and STEM educators. Flick and Bell (2000) stated that many pre-service science teachers are first introduced to various technological tools in the program, and then a general educational technology course that covers the practices that need to be applied in science classes. Instead, technology should be introduced in the context of science and STEM teaching as a tool to support meaningful science learning. This approach is more closely compatible with the transdisciplinary role in which science teacher educators consider tools and technologies that not only represent the work of scientists and other STEM professionals, but also directly support the understanding of science content.

Today, engineers carry out their work on a project basis. Project-based learning method is essential for environments where engineering design skills will be revealed in order to train individuals who think like engineers. In this way, students or team members try to minimize the product's error while producing the best solution (Çallı, 2021). These concepts also allow for opportunities for rich mental processes that will reveal 21st century skills such as financial literacy. Students work together to create innovative solutions to real-world problems and share their solutions with others. In addition to the student’s individual development, the interaction with the social environment especially gives the opportunity to use technology at a high level. In technology-supported environments, teamwork created with concepts such as paired programming is fundamental in terms of the formation of synergy and the development of skills that enable doing things together in the best way. As they carry out their research and projects, they must access, analyse and use the information they need in order to complete their learning tasks. While students are working on the task, they must develop essential life and career skills by learning to manage their time, be self-directed workers, and collaborate effectively with others. Using the appropriate technology tools to complete their tasks, students discover the most effective and efficient ways to access and manage the digital information world available to them.

In the transdisciplinary role of technology, 21st century technologies are seen as an empowering element and included in the process. The contributions of popular STEM initiatives such as popular science, science centres, robotics competitions, and the maker movement to the STEM: Integrated Teaching Framework are noteworthy (Çorlu, 2021). Technology integration should be seen as an approach aimed at examining all the changes people make in the natural environment for their own purposes (Dugger & Naik, 2001). Some of the important technologies and learning approaches in the 21st century include 3D printers, augmented reality, artificial intelligence and gamification. 3D printing technology has a rich structure that can support the homogeneous coexistence and interconnectedness of the disciplines in STEM. 3D printing technology creates a platform of application combined with virtual and real education innovation to make up for the lack of traditional teaching equipment and enhance students' spatial abilities. The innovative features of the 3D printing model allow students to explore the innovation skills advocated by STEM education. In geometry subjects, it can abstract complex three-dimensional geometry through visualization to encourage students to internalise knowledge. The transdisciplinary role of technology emphasizes innovative three-dimensional transdisciplinary STEM education through the introduction and application of

3D printing technology. Augmented reality has the potential to merge reality with the virtual world. AR is a technology that enables the interaction of reality with the visualization of virtual graphics, making it possible to create virtual environments that directly or indirectly overlap with a real environment (Velázquez & Méndez 2018). Augmented reality can be viewed as a didactic tool that contributes to the transformation of learning modes. Since AR is a system that allows for the manipulation of 3D objects and extraction of information from a real environment, this technology enables both teachers and students to see information in a real environment that would be impossible to display and allows for the visualization of many scientific concepts that were hitherto impossible to clearly demonstrate. (Velázquez & Méndez, 2018). Augmented reality is of great importance in the transdisciplinary role of technology in STEM education. Emerging applications of artificial intelligence, another cutting-edge technology, comprise a variety of disciplines, from medicine to manufacturing and especially education. AI applications in education support learning with options such as smart education system (1), personalized environments for learning experiences (2), and supportive tools for teachers to deliver high-quality education (3). Beyond applying AI as educational tools, AI-assisted robotics applications are becoming more important in raising students who think like engineers or scientists. In transdisciplinary STEM integration, it is regarded as essential for students to make connections between emerging technological solutions such as artificial intelligence and real-world problems (Maule, 1998; Freedman et al., 2000; Bundy, 2013). Given the complexity of AI and the technical background knowledge required to understand AI, the need for more than one discipline serves for interconnected wholeness understanding and provides an opportunity to reveal the transdisciplinary role of technology.

Technological evolution (paradigm shifts) presents new risks along with all its opportunities. New XR technologies, namely virtual reality and augmented reality technologies, are becoming widespread and opening a new avenue for STEM applications. Things that are too dangerous or expensive for children and teenagers to do in real life (*like using hazardous chemicals, working with laboratory equipment*) can now be simulated in immersive environments. A simulated learning environment can strengthen the cognition and motivation of learning and make learning more effective (Kim et al., 2015; Stull et al., 2018). The combination of creative and advanced technologies and teaching can increase students' STEM learning engagement and improve their learning attitudes towards STEM. Therefore, it helps students to perceive scientific concepts and solve interdisciplinary problems through creatively simulated and uninterrupted experiential learning environments (Katehi et al., 2009). General and STEM-oriented gamification studies report an increase in students' learning performance as well as in their motivation and participation (Ortiz Rojas et al., 2017).

CONCLUSION

While the developed countries are trying to adopt innovative perspectives in the field of education in order to have a greater say in the new world race that requires different skills, the industry sector and the society expect today’s students who will form the workforce of the future to be individuals who can think flexibly and productively, who can produce information, who have foresight about where to use the information produced, who can have critical perspectives towards the events they encounter, who can work in groups, who can cope with complex and different problems; rather than being individuals who have no idea about where and how to use an answer they have found as a result of working on a given problem (Cansu & Çakıroğlu, 2020).

The great leaps and advances in technological developments in the 2000s show that technology can play a vital role in supporting not only itself but also education. With this understanding, Mishra and Koehler (2006) expanded Shulman's (1986) pedagogical content knowledge and added a third area as technology to the model and defined the intersection of these three areas as technological pedagogical content knowledge. Mishra & Koehler (2006) still continue to develop the TPCK framework as a conceptual model with theoretical, pedagogical and methodological implications for educators who try to use technological tools as educational or instructional technology.

RECOMMENDATIONS

The authors view this theoretical framework as an effective frame that allows for the development of integrated interdisciplinary STEM courses. To clarify the problems that exist in integrated transdisciplinary STEM learning, a variety of implementation strategies are needed. The role technology and engineering play in the broad spectrum of the STEM movement may not be straightforward for many STEM educators. Despite the studies conducted in the last century, there is still no consensus on the essence of the role of technology in education. This study is an example of the second type in Repko's (2008) classification of interdisciplinary STEM integration studies. According to Repko (2008), facilitating interdisciplinary research, which is the second type; aims to develop a basic understanding or a path to follow for the future by combining knowledge, techniques, tools, perspectives, concepts, theories, and results from two or more disciplines. It also intends to produce solutions to a problem that can be solved beyond the perspective of such a single discipline. There is a need for further research on the other types in Repko's (2008) classification, which is carried out by taking into account the characteristics of this theoretical framework.

For teachers to support their students in the engineering design process, they need to know about the learning objectives. Further studies about how transdisciplinary STEM will be integrated are needed during the next several years, so teachers would know how they could integrate it into their lessons.

We cannot know the effects of and the requirements for integrated transdisciplinary STEM Education without implementation. How can integration support students' learning? What kind of support is needed for lesson integration? What kind of curriculum is possible? What student outcomes can be identified in integrated learning? To find answers to these questions, the authors plan to continue their project and expand the collaboration with teachers in schools. Therefore, future research into STEM Education should be in the form of innovative design research that addresses the needs of teachers who will be needed in the technology classrooms of the future. It seems that the impact of technologies specifically needed for the acquisition of science in STEM education is still largely provisional and teachers face difficulties to ensure a meaningful exploration process. Both teachers and students use technologies mainly reproductively (to seek information on the internet, summarise it, and make a presentation) as consumers of information and less productively as developers of knowledge. Technology is only a tool and its meaningful use depends on the teacher. Effective technology integration in transdisciplinary STEM involves the ability to not only enhance teaching and learning but to promote higher order thinking skills as well as other 21st century skills that are important for student success.

It is thought by the authors that this study can be a bridge for the transition from transdisciplinary understanding to metadisciplinary understanding at Williams et al. (2016) integration levels.

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