*International Forum*
*Vol. 24, No. 2*
*December 2021*
*pp. 5-20*

*FEATURE*

# Nurturing Engineering Habits of Mind in the 21st Century Learners

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**Abstract.** *The 21st-century community expects schools to equip students with skills like creativity, collaboration, effective communication, ethics, optimism, and systems thinking. These life skills are also referred to as engineering habits of mind (EHoM) that engineers use when they solve societal problems that impede progress. They are not, however, richly cultivated in STEM classroom practices. Students' learning is not often aligned with the demands of life beyond school. This theoretical paper explores the six engineering habits of mind that need to permeate students' learning, such as systems thinking, creativity, collaboration, communication, optimism, and ethical considerations. An ill-structured (having no clear direction to a solution) problem-solving approach is deemed significant in developing EHoM. Such nurturing calls for a re-engineering of the teachers' instructional practices to draw relevant support from the administration, parents, and community to promote efficacy.*

**Keywords:** engineering habits of mind, engineering design challenge, teacher support, school leadership, community partnership.

## Introduction

Children are raw engineers. In their play, they build and manipulate kinds of objects in the world around them, from piling toy blocks into a tower to designing them in various shapes. They experiment, create, and fix until they are satisfied with the outcome. A sense of pleasure and excitement is felt as they interact with each other and the things around them (Lucas, Hanson, & Claxton, 2014). However, when they come to school, the passion to create, design, and collaborate is not always cultivated. They are seated in silos to listen while the teacher is speaking and to mind their work instead of discussing it with others (Freire, 2005).

Willingham (2010) says that teachers do not understand how students learn best; hence, students do not like school at all.

Teaching and learning in the 21st century require a different approach because what is often happening inside the classroom is far different from the activities in the society that students interact with daily. This is a call to align classroom practices with real-world applications to make learning more meaningful (Honey, Pearson, & Schweingruber, 2014). Heick (2019), describing the attributes of efficient academe, states that as human civilization evolves, its working components should also advance. This advancement involves rethinking in thecultivation of life-long skills like engineering habits of mind that students can draw on when they are confronted with life challenges.

## Background of Engineering Habits of Mind

Habits of Mind (HoM) are collections of life skills and dispositions that are developed over time through various experiences in school and daily life. They are the immediate ways, actions, and reactions people use and draw on when they are confronted with any challenges and difficulties (Costa & Kallick, 2002, 2008). Resnick (1999) adds that these habits are intelligence in practice. HoM involves looking for strategies and solutions to understand processes and make things work better. Hence, “HoM is the sum total of one’s intelligence” (Resnick, 1999, p. 39). They are worth considering and developed.

Sixteen HoM are distinguished by Costa and Kallick (2008): (a) persisting, (b) managing impulsivity, (c) listening with understanding and empathy, (d) thinking flexibly, (e) thinking about your thinking (metacognition), (f) striving for accuracy, (g) questioning and posing problems, (h) applying past knowledge to new situations, (i) thinking and communicating with clarity and precision, (j) gathering data through all senses, (k) creating, imagining, and innovating, (l) responding with wonderment and awe, (m) taking responsible risks, (n) finding humor, (o) thinking interdependently, and (p) remaining open to continuous learning. These HoM are referred to as thinking skills that can be embedded in the curriculum content such that content becomes a medium to exhibit the habits and develop them among students.

Habits of mind connect the different learning areas that support the transition of learning experiences from elementary to university (Hanson, 2017). They are intellectual behaviors that are widely cultivated in the US education system (Lucas et al., 2014). Related to HoM are a set of skills that are important for those who are training in the field of engineering. The National Academy of Sciences situated six engineering habits of mind (EHoM) to be at the core in engineering education within the K to 12 STEM curriculum. These are systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (Honey et al., 2014). These EHoM are described as what engineers think and do when they solve societal problems while creating ways to make life easy and comfortable (Lucas & Hanson, 2016). These are the necessary skills in the scientific and technological society of the 21st century. Hence, these are closely associated with science and mathematics education. Each EHoM is discussed further in this segment.

## Systems Thinking

The term systems thinking is coined by Richmond (1994). It is defined as making a valuable prediction of behavior through a profound comprehension of the root of the construct and seeing the interconnectedness of the elements of things. Senge (1990), on the other hand, said that systems thinking is about looking at the various components of the structure, seeing that one cannot function without the other. Considering these two definitions, Arnold and Wade (2015) provided a description of systems thinking.

> Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system. (p. 675)

This vivid definition of systems thinking permits a reflection on how to incorporate it into class instruction. Senge (2006) advises that the key to educating learners in systems thinking is to provide tasks in a progressive degree of complexity with a high degree of personal alignment in their lives. This is exactly what Jerome Bruner prompted, a spiral learning that is widely practiced in the K to 12 curricula. Hence, cultivating young creative minds should involve developing their systemic perspective progressively.

## Creativity

Getting students to succeed in school goes beyond teaching the three Rs of learning; rather, it is about determining clever choices and uses of the resources available (Flora, 2019). Creativity is generating something non-existent like an innovative technique or a problem solution which can be an ingenious piece or practice (Kerr, 2016), a key component in innovation. Lucas et al. (2014) proposes that creativity is inherent among youth; however, due to teachers' practices that do not tap into these EHoM, the skill "lies dormant in most students" (Liu & Schonwetter, 2004, p. 806). Students display a lack of interest in learning and are hesitant to participate in class. Therefore, the teachers must awaken and nurture the creative minds of the students through facilitating various "thinking tools" (Liu & Schonwetter, 2004, p. 804). Through this nurturing, students can become productive in their everyday lives and practice success.

## Optimism

Optimism is an unwavering disposition that includes being positive, resilient, and adaptive to transforming conditions. It has various impacts on life—a happy disposition and a productive lifestyle (He, Cao, Feng, Guan, & Peng, 2013). Seligman (2006) shares approaches to develop optimism among children. One is to look at the link between adversity, belief, and consequences, the ABC link. This approach can be practiced and processed until the learners' belief changes. When this happens, the consequence also changes. Generally, optimistic parents have optimistic kids, and optimistic teachers have optimistic students.

To developing optimism among students is to provide their contexts of experiences that allow them to think and imagine that things can be improved in some ways (Katehi, Pearson, & Feder, 2009). Nurttila, Ketonen, and Lonka (2015) found that students with high optimism and a sense of competence had the lowest task avoidance; hence, they had better academic achievement. Teachers are to provide challenges that support students' desired learning unless students' eagerness to learn wanes and lack of interest to participate in any school activities may occur, such that they become disengaged in learning. This support provided also relates to the concept of scaffolding and zone of proximal development developed by Sovient psychologist Lev Vygotsky.

## Collaboration

Collaboration is a "joint effort toward a group goal" (de Vreede, Briggs, & Massey, 2009, p. 122), the practice critical for engineers, researchers, and technologists because it "leverages the perspectives, knowledge, and capabilities of team members" (Katehi et al., 2009, p. 7). Collaboration promotes productivity in various professional works and expedites tasks. Slavin (1980) cites that it can enhance students' social skills due to the interaction within the group, increase student achievement, and boosting self-esteem. Despite its encouraging values, it does not thoroughly permeate the educational setting especially in many non-Western countries.

## Communication

Ethics describes proper and just principles; it pertains to good moral judgment (Kallenberg, 2013). Polonsky (2005) discusses that ethical aspects that require an evaluation of benefits to its constraints. It is a responsibility to ensure that no physical, psychological, or social harm has been done to people and the community due to any innovations. Sokol (2017) says that discussing ethical considerations among students is relevant. Although it may be overwhelming to young minds but awareness of the possible impacts technological advances have on people and the environment is a component that needs to be emphasized. This emphasis allows students' rethinking of their decisions as they create and design valuable contributions to problem solutions in society. They are to consider trade-offs and constraints (engineering design expressions) in their projects and be reminded that it is always wise to design solutions that are "people-first technologies" (Sokol, 2017, para. 4). In the long-run, the development of such moral judgment is worth all the efforts.

Some guidelines to make distinct ethical decisions are suggested: "(1) identify the issues (what) and the stakeholders (who); (2) analyze the alternative course of action from consequences, intent, and character perspectives; (3) correlate perspectives; and (4) act on your decision" (Stephan et al., 2015, pp. 45-46). At the heart of any innovation is an ethical code requirement that prioritizes honesty and integrity. STEM teachers are to instill this in the minds of the students as they formulate solutions to real-life problems. Getting students into the habit of behaving intelligently leads to the practice of intellectual behavior and productive actions (Costa & Kallick, 2008). Hence, EHoM should be cultivated throughout school life. The way an individual think affects beliefs, jobs, and background. To improve one's thinking is to develop various ways of thinking (LeDoux et al., 2014) like EHoM, and these should be embedded in the curricular instruction.

## Permeating EHoM Development in Instructional Practices

Teachers' instructional practices are crucial to the success of nurturing EHoM. Aglazor (2017) says, "Good teaching practice is a key influence on student learning" (p. 101). It is about the rethinking of the approaches to teaching (Lucas, 2015). Although there is no such thing as the best one-size-fits-all, there are practices supported by empirical studies that promote students' EHoM development. These should be permeated in the teachers' instructional practices. Lucas and Hanson (2016) considered problem-based learning (PBL) and project-based learning (PjBL) as potential strategies to develop EHoM among students.

PBL or PjBL problems vary in complexities (Jonassen, 2011). Some are ill-structured, while others are well-structured. One of the signature pedagogies that works in conjunction with PBL and PjBL is the engineering design challenge (Jonassen, 2011; Hynes et al., 2011; Lucas & Hanson, 2016). Jonassen (2011) considers it as the most ill-structured and complex (as cited in Householder and Hailey, 2012), but the resulting achievement of the students is remarkable (Kapur, 2011).

Another arena to consider in permeating EHoM development is establishing teacher support. Teacher support incorporates wider involvement from the school and the community. The engineering design challenges and teacher support are vividly explained in the next segments.

## Engineering Design Challenges

Engineering design challenges as “ill-structured problems” (Householder & Hailey, 2012, p. 2) are based upon the common problems that touch the well-being of the people in the community. The term engineering refers to what engineers think when they are solving societal problems while utilizing science, technology, and mathematics. Design, on the one hand, refers to what engineers do when solving societal problems that include designing and innovating products or any artifacts that man uses to improve life. On the other hand, the challenge is inviting students to find solution/s to real-life problems bombarding the “human-made environment” (p. 2). Ill-structured problems are challenges with multiple solutions; thus, students tend to work collaboratively rather than competitively.

The engineering design process (EDP) is a step-by-step iterative process that engineers follow when finding solutions to problems. Hynes et al. (2011) describe the competencies linked with the design challenges for high school students (See Figure 1). It is proposed as a conducting guideline for high school instruction. The steps of EDP are explained herein.

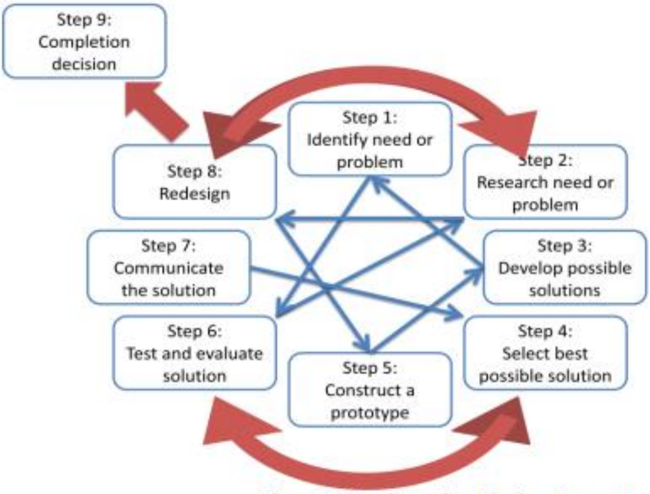

**Figure 1 Engineering Design Process**

Figure 1. The engineering design process model.

Note: The engineering design process model. Adapated from “Infusing engineering design into high school STEM courses by M. *Hynes et al. (2011), p. 9.*

**Identify and define problems.** The problem to be solved should be ill-structured and open-ended; thus, multiple solutions can be drawn. Shin and McGee (2003) and White and Frederiksen (1998) specify that problems should be meaningful to students' life, something that pertains to real-life applications and not just memorization. When presented with this kind of problem, students' practice "critical thinking skills" (Hynes et al., 2011, p. 10), which suggests that they are discovering solutions to real-life problems and showcasing their creativity. Besides, while identifying a solution to the problem, students have to identify the constraints of the design artifacts and align innovations with the user's expectations (Hynes et al., 2011).

**Research the need or problem.** Researching is a must when finding a solution to a problem (Ennis & Greszly, 1991). Hynes et al. (2011) emphasize that rushing while finding a solution to a problem is not applicable in engineering. Instead, it takes the identification of various factors that contribute to the problem; hence there is a need to explore the possibilities of the various solutions before making a decision. With this process, students can distinguish the best solution and innovation.

**Develop possible solutions.** Problem-solving is at best, a collaborative task. Engineering design challenge requires teamwork (Honey et al., 2014). Wendell (2008) refers to it as active engagement where students brainstorm, plan, and create illustrations or depictions of the solutions to the problems. While engaging in an interactive discourse with one another to look for valuable solutions, students practice communication skills to enunciate the possible solutions and refine them while identifying further trade-offs (Hynes, 2012). Documentation is also vital in this step for reference when a review is needed (Hynes et al., 2011).

**Select the best possible solution.** This step is the decision-making process, and the proposed solution shall be supported with research and evidence (Dym et al., 2005). Hynes (2012) says that it should address the core issue being studied. Students at this step are seen tinkering to arrive at the best possible solution.

**Construct a prototype.** This is the stage of putting the planned solution into a concrete form. Carberry et al. (2009) refer to this step as the construction of the model for the solution to the problem. This step may be a constant comparison and refinement of the model until the desired functionality of the solution is attained (Koehler et al., 2005).

**Test and evaluate the solutions.** Testing and evaluating identify constraints and trade-offs to effectively improve the design artifact (Hynes et al., 2011). This is a point of experimenting whether the designed solution to the problem is viable (Trevisan et al., 1998). Herein, the students may distinguish if the solution adheres to the requirements of the needed product or innovation.

**Communicate the solutions.** This is the point that students share their ideas with other students, teachers, and mentors through a presentation. Gassert and

Milkowski (2005) advise that the presentation should include "specifications, performances, issues, limitations, and constraints" (as cited in Hynes et al., 2011, p. 11) and should be well documented. Science and math fairs, oral presentations like schools' conferences, and other school-related events are a potential milieu that help students to receive feedback from fellow students, teachers, and mentors who can be engineers as well. Receiving various comments and observations can help in the construction of a better report and output that Gentili et al. (1999) mentioned as achievable by high school students.

**Redesign.** Koehler et al. (2005) describe this step as the optimization process. This is the period of incorporating suggestions and feedback from the testing and presentation while meeting the needed yardsticks for the final output or product (Hynes, 2012). The output may undergo alterations to produce the most successful model.

**Completion decision.** This is the final decision for the output of the engineering design challenge that undergoes constant assessments for weaknesses and flaws. Hynes et al. (2011) suggest that if it can be decided as the final product that satisfies the product innovation specification, then it is ready to be implemented. The iterative process of EDP also allows the designer to revisit areas for improvements until the desired output is reached (Householder & Hailey, 2012).

The engineering design challenge utilizes skills such as creative thinking and action, analytical reasoning and communication, and collaboration while testing for solutions. This application reflects how engineers think and act while solving societal problems (Lucas & Hanson, 2016). The development of this kind of thinking—the engineering habits of mind where students are problem solvers—prepare students for an active role in life beyond school. Hanson (2017) proposes that teachers' practices should allow "understanding of the habit; engagement and commitment to the habit; opportunities for the habit to flourish; and transfer of the habit" (p. 9). Thus, teachers' role is critical for students to develop these skills.

Without teachers' guidance in implementing the design challenge, the students might not develop the skills of making creative solutions to real-life problems, and the opportunity to learn such habits may be missed out (Sneider, 2012). With this, teachers have to be equipped with knowledge and skills in employing this kind of learning experience. In the same manner, support from the administration is expected if the goal for students' achievement in developing EhoM is to be reached.

## Teacher Support

Teacher preparation is crucial to effective teaching. The Community for Advancing Discovery Research in Education or CADRE (2011) identifies five points to consider to support teachers in preparation for a successful teaching-learning process. These include the following:

1. Teacher training should include context, pedagogies, and empirical studies on how students learn.
2. Training should be aligned with the district-specific curricula so that teachers are learning what they actually will be teaching.
3. Professional development must address teachers' classroom work and the problems they encounter in school settings. Use new strategies in teaching and reflect on your practice and discuss it.
4. Professional support should permit regular interaction and collaboration with colleagues and school leaders, such as professional learning communities.
5. Teachers need multiple and sustained opportunities for continued learning over a substantial time interval (pp. 4-5).

Teacher preparation, induction into the profession, and continued professional development are factors that support the teachers (Wilson, 2011). Teacher preparation necessitates teachers understand the curriculum to be taught. Hence, an in-depth teacher's knowledge of the subject matter provides better opportunities to plan out an effective strategy in teaching the content. Stohlmann, Moore, and Roehrig (2012) state that teacher's pedagogical knowledge promotes students' engagement, thus, making learning more meaningful. Moreover, teacher training should be a continuous process from preparation, induction, and professional development. Capitalizing on teachers' competencies produces a constructive influence on students' learning and accomplishment that can result in cultivating a strong school system (CADRE, 2011).

**School leadership.** School governance, workforce cooperation, and a positive working environment are keys to successful school organization and instruction (CADRE, 2011). Allensworth (2011) cites five basic supports for effective school improvement. They are "school leadership, strong professional capacity, parent-community ties, student-centered learning climate, and instructional guidance" (CADRE, 2011, p. 2). A more distinct observation related by Allensworth, Ponnisciak, and Mazzeo state that "good teachers cannot be effective in schools that lack a supportive climate … they leave if they do not believe they can be effective in a school" (as cited in Beatty, 2011, p. 49). This evidence shows that teachers' support is essential in establishing a strong school organization and instruction.

Besides, Marzano, Frontier, and Livingstone (2011) adds that not only teachers should undergo professional training but also the school administrators since they make decisions for the provisions of the instruction. School leadership plays a vital role in producing expert teachers. Shernoff et al. (2017) identify the leadership support needed by the teachers to establish strong instruction. These include "provision of resources and technology support, support for collaborating and planning, professional development" (Shernoff et al., 2017, p. 7), and supportive school culture. Hence, effective instruction is not solely the teachers’ responsibility but of the leadership as well.

Community partnership. Partnership with the community should be an integral part of education. Using the ecological metaphor, Erdogan (2014) revealed that a successful learning environment involves a collaborative action of the community consisting of well-trained teachers, community leaders, students, and experts. The students, teachers, community leaders, and experts are the actors in the ecological system, the classrooms are the contextual arena of learning, and cooperation is the interaction of the actors. Marshall (2010) refers to this as the learning ecosystem where the community is involved in students’ education while embracing Leadership, Innovation, and Knowledge (LINNK).

The Committee on STEM Education of the National Science and Technology Council (2018) reported that one of the strategies for success is to cultivate networks between the education sectors and the community. “It is important to increase work-based learning and training through educator-employer partnerships” (p. 9). Lynch et al., (2013) also emphasize the same principle adding that the supply of an effective workforce in the community is dependent on the quality of training the schools provide. This partnership can address the workplace expectations of the skills required, hereby closing the skills gap and resulting in better preparation for employment. There is a call for joint partnership with interested stakeholders to engage and be involved in the training of youth who will replenish the various significant positions in the civic society from local to global.

Lucas and Hanson (2016) propose that integrating the world of work with learning provides awareness of real-world practices. This integration is beneficial to students because there can be a transfer of interest and enthusiasm from the expert to the students. Role modeling and mentoring are also highlighted in this practice.

In summary, teachers’ approaches to learning are crucial to the development of students’ EHoM. The development of students’ EHoM is a process that requires the repetitive practice of problem-solving through engineering design challenges. For the teacher to optimize the learning experiences of the students, teacher support is needed. The school leadership has to ensure that certain provisions are within reach. There should be an allotted time for teachers to plan and collaborate, professional training that specifies what to do in the real class setting, and a positive learning environment in which all stakeholders contribute to the success of the learning process, specifically the community.

## Conclusions and Recommendations

The education system and instruction do not generally practice the development of students' EHoM. Thus, a paradigm shift that allows students to collaborate and take the role of problem-solvers tackling relevant problems in everyday life is an opportunity the 21st-century learning community requires. This takes a paradigm that is far from being procedural, instead it requires something that is toward ill-defined problem-solving. Kapur (2010) warn that this may be perceived as failure initially as students may struggle from this learning experience. However, the frustration can be a "productive failure" ( Kapur, 2010, p. 523) and a deeper learning experience that improves the problem-solving abilities of students.

The engineering design challenges and teacher support such as school leadership and community partnership are deemed beneficial in developing students' EHoM. Teachers, administrators, and the community, including parents, mentors, and even employers, are to provide opportunities to develop these skills. A positive learning environment that encourages students to take responsibility for their learning should be instituted. Also, permitting some struggles in instruction capitalize on students' creativity, communication, collaboration, systemic thinking, optimism, and ethical considerations.

Hence, there should be a shift in teachers' disposition and attitude toward teaching. Also, the efficacy of instruction lies in the provision of various teaching resources needed in the learning experience, such as space for the design challenge and the equipment and supplies. The teacher has to develop problems according to the level of the students. In creating teams, the teachers should diversify the members according to their capability as each one is accountable for the learning of the whole group while positive interdependence is promoted. Since the problem is ill-structured, the teacher has to scaffold the learning experiences from simple toward an increasing level of complexity. The design project should have benchmarks that provide direction for testing and evaluation. Finally, the design challenge should be sensible and practical that students can relate to the relevance of what they do to the concepts they learn. This practice is not about designing a challenge to suffice the need for hands-on activities; instead, it is about making learning realistic and applicable to daily life. Further exploration of the engineering design method of teaching in qualitative research using action research that tests engineering design in the classroom setting for student achievement is recommended.

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