Re-positioning Science Instruction for the 21st Century: Development of Instructional Materials of Integrated Science, Technology, Engineering and Mathematics Approach for Secondary School Students

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Researchers have achieved consensus on the need for a paradigm shift in the process of education in the 21st century. Shift from learning what is convenient to quality learning and functional education is needed now and for the future. This will help learners develop skills and competencies relevant to the 21st century digital age. However, teachers lack the knowledge and instructional materials to implement innovative instructional approach for the digital age because they were mostly trained to implement the traditional model of instruction. Hence this paper attempts to re-position science instruction for the 21st century through the use of an Integrated Science, Technology, Engineering and Mathematics Approach (ISTEMA) instructional material for secondary school students. This approach is expected to enhance learners' acquisition of relevant skills needed for careers in the 21st century digital age. This paper further seeks to establish the gap between the observed classroom practices and the expected in the 21st century and how this instructional material will help bridge the gap. The conceptual framework for developing ISTEMA is based on instructional design and learning theories. The ISTEMA to instruction which is a learner centered five phase model was developed based on consensus of features for integrated instruction from the research literature.

Keywords: *21st century skills, Integrated STEM approach, Instructional material, Secondary education*

Worldwide, now more than ever, countries are seeking ways to improve their economies and wellbeing through innovations such as new energy sources, improved goods and services, information management and communication. Others include mitigating the impacts of environmental and social problems and taking advantage of emerging employment opportunities in the digital era. These can only be achieved through developing a human resource with 21st century skills (Honey, Pearson, & Schweingruber, 2014; Walshe, Johnston, & McClelland, 2014). It cannot be overemphasized that, human resource development is the vital key to viable economic and technological survival in the digital age. Therefore, students and potential employees are expected to acquire 21st century skills and competencies such as critical thinking skills, creative skills, collaborative skills, communication skills, problem solving skills and innovativeness. Some of these skills are identified as four super skills, critical thinking, creativity, collaboration and communication (4cs) (Kivunja, 2015, p. 21). The relevance of these skills places demands on the schools to produce individuals with skills that will respond appropriately to the demand or societal needs.

However, the educational practices in our secondary school classrooms are traditionally based, *focusing on recall of facts, memorization and standardized testing. Nevertheless, premium* in today's society is not on passing standardized test and recall of facts, but on the acquisition of relevant skills and the application of what is learned in the classroom to solve real life problems. Skills needed to solve present and impending economic and social challenges as well as compete effectively in the global market (English, 2016; Honey et al., 2014; Prinsley & Baranyai, 2015).

Consequently, the process of education and instructional approaches in particular need to be re-positioned. Approaches that will enhance the production of human resource that will identify and engineer solutions to the needs of the society in the digital era (Shah, 2010; *Thompson, 2011). Hence the need for Integrated Science, Technology, Engineering and* Mathematics Approach (ISTEMA). Nevertheless, there is no consensus among researchers on the definition of integrated STEM approach. The several definition ranges from disciplinary, multidisciplinary, transdisciplinary and interdisciplinary as well as the integration of two to four STEM discipline (Breiner, Harkness, Johnson, & Koehler, 2012; Honey et al., 2014; Vasquez, Sneider, & Comer, 2013). Other ranges from content to context integration (Corlu, Capraro, & Capraro, 2014; Kertil & Gurel, 2016).

Therefore, the integrated STEM approach in this work involves the combination of two or more STEM disciplines to learn an instructional content from a given discipline while appropriate context from two or more disciplines is use to deepen the understanding of the learning content among secondary school students. Becker and Park (2011) carried out a meta-analysis to investigate the influence of STEM integration types; their findings revealed that the integration of the four disciplines of STEM has the largest effect size of 1.76, technology and science yielded an effect size of 0.23, while the integration of engineering and mathematics yielded the least effect size of 0.03. However, Becker and Park (2011) did not report the mode or context *of integration among the four disciplines and the instructional framework used, however* the integration of the four, science, technology, engineering and mathematics enhances students learning more.

Statement of the Problem

In view of the global importance given to STEM education many countries are questioning their processes of education with a view to enhancing integrated STEM approaches for the development of 21st century skills. This new approach reflects the way STEM concepts and HOTS are applied by STEM professionals (scientist, engineers, technologists and mathematicians) to solve problems. The global society of the 21st century is facing problems that are multidisciplinary in nature, such as environmental challenges, resource control and poverty. Finding solutions to these problems requires the application and integration of knowledge and ideas from different STEM disciplines by individuals that can think critically.

However, the teaching of STEM subjects in secondary schools is in isolation with emphasis on lower thinking skills (LOTS) while the expected skills are higher order thinking skills. Instruction in secondary school is dominated by the traditional instructional model that is teacher centered, *which has resulted in dwindling performance among secondary school* students. There is, therefore, an instructional incongruity between the skills students acquire in school and the skills expected to solve real life problems similar to the way STEM professionals solve problems. Consequently, the need to try the integrated STEM approach is an innovative instructional approach with the potential to help; therefore teachers may not be able to implement it due to lack of instructional framework (Kimmel, Carpinelli, Burr-Alexander, Hirsch, & Rockland, 2008; Rockland et al., 2010).

The rationale for integrated instruction is because the teaching and learning of single-subject has a negative effect on the learners by firstly, providing disjointed and incoherent ideas, facts and skills that may not be relevant in solving problems in real life. Because problem solving in real life requires the integration of knowledge and skills from more than one discipline. In view of this, it is reported that the traditional approach of teaching subjects in isolation will not meet the needs of learners in an inter-reliant society (Mason, 1996).

Literature has reported the potential of STEM education, among others, to include helping learners to be critical thinkers, creative thinkers, innovators, inventors and problem solvers. (Brown, Brown, Reardon, & Merrill, 2011; Morrison 2006; Robelen, 2011). It deepens the understanding of science and mathematics through engaging the students in real world problem solving, minds-on and hands-on activities approach as well as collaboration (Davis, 2011; English & King, 2015; Kertil & Gurel, 2016).

Hence the need to prepare an integrated STEM approach instructional material for implementation in secondary schools. This may deepen their understanding of the instructional content and link what is learnt in the classroom to real life.

Integrated STEM Instruction

Research in integrated curriculum and instruction has been done for decades (Berlin, 1994; Bybee, 2010; Masson, 1996; McBride & Silverman, 1991; Prinsley & Baranyai, 2015; Tsupros, Kohler, & Hallinen, 2009; Wallace, Malone, Rennie, Budgen, & Venville, 2001). However, integrated instruction has gained more relevance and prominence with the advent of STEM education and its relevance for an individual's meaningful learning. It has attracted attention globally in view of its benefits in motivating learning, improving achievement and helping learners to be better prepared to solve problems.

The proponents of the integrated STEM approach argue that it creates curricular links during learning which help to deepen conceptual understanding. Integration of the engineering design process in secondary schools will improve students' achievement in mathematics and science, enhance their understanding of the engineering design process and awareness of engineering concepts. Research literature have reported that the integrated STEM approach increases students' attitude and interest in academic task and engages the learners' cognitive skills and promotes higher order thinking skills. Because the approach is characterized by problem solving, questioning and team work (Fantz & Grant, 2013; Gallant, 2010). This will create a learner centered environment which will engage them actively.

However, those who opposed integrated STEM approach did not object to the superiority of integrated instruction over single subject instruction, but believe that the traditional curriculum is rooted in the culture of the people. Therefore, suggestion for change will be resisted by stakeholders, especially teachers (Sanders, 2009). Furthermore, teachers may not be able to implement the approach for obvious reasons such as lack of instructional framework and the present school system favors a traditional model of instruction; hence the approach may not yield the desired results. Consequently, the instructional framework developed here will help teachers overcome these challenges because it is flexible and can fit into the traditional model since it is context based STEM integration.

In the context model of STEM integration, science or mathematics learning content is given a prominent role, relevant principles or concepts of other STEM disciplines serve complementary roles to deepen understanding of the learning content (Corlu et al., 2014). For example, Genetics an instructional content in science is the primary instructional content, while engineering and technology in the form of engineering practices and design process are applied, mathematics in the form of probability and algebraic thinking is used to deepen the understanding of genetics and in the process develop relevant skills as illustrated in Figure 1:

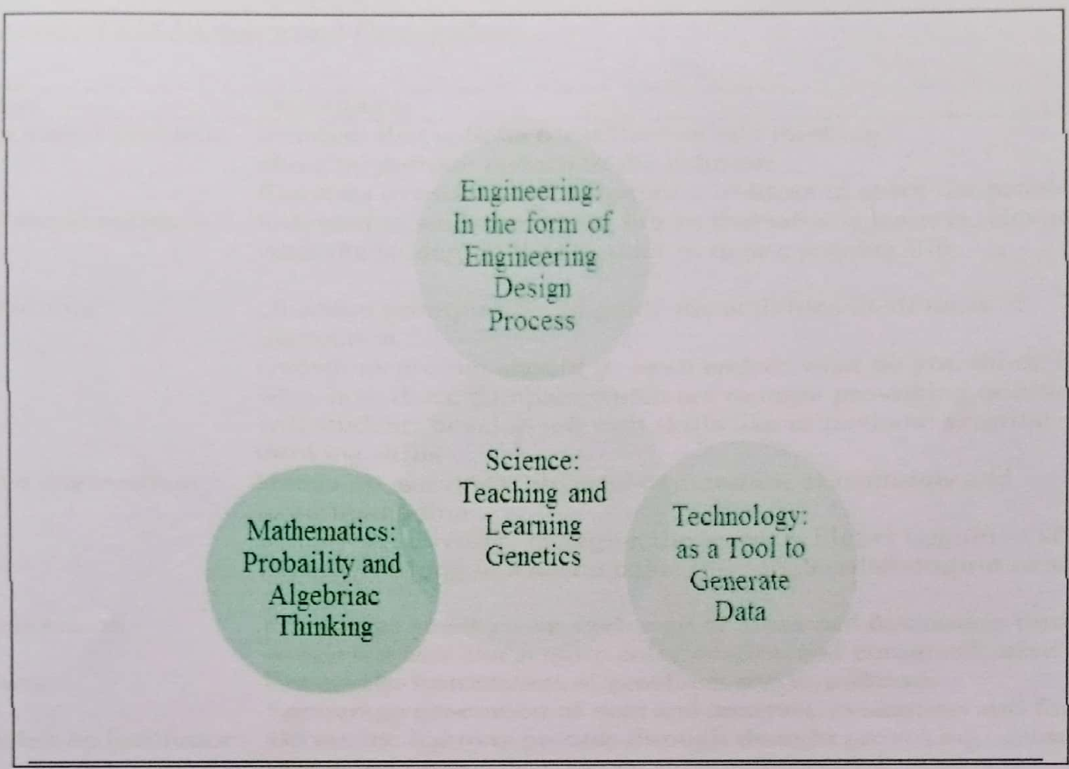

Figure 1. Illustration of context based stem integration

ISTEMA Framework

The preparation of Integrated STEM Approach (ISTEMA) instructional material was supported by the constructivist learning theory which emphasize learners' active engagement in the learning process. The learners' cognitive processes are also engaged which will lead to the development of 21st century skills. The features of constructivism employed in the preparation of ISTEM material small group interaction or collaboration, student' centered and active learning. Furthermore, the instructional material preparation was also supported by instructional design theory; orderly procedure of arranging resources to enhance instruction. Therefore an instructional model offers the basis to translate a learning theory into an instructional material. The module's guide includes; instructional resources, activities, and assessment strategies (Smith & Regan, 1999). The Dick, Carey, and Carey (2001) instructional model is adopted because it is popular and important, it adopts the conventional elements of analysis, design, development, implementation and evaluation (ADDIE) with each stage is directed towards achieving the learning objectives.

Features of ISTEMA

There is a convergence of research literature on some common features or characteristics of integrated instruction which will enhance learners' development of relevant skills of the 21st century (English & King, 2015; Frykholm & Glasson 2005; Furner & Kumar, 2007; Reeve, 2013; Treacy & O'Donoghue, 2014). From the literature the following features were adapted and adopted to form the basis for preparing integrated STEM approach instructional material, the features include; open ended problem, questioning, collaboration, active engagement, inquiry and teacher as facilitator as well as hands-on and minds-on activities. The features and their descriptions are highlighted in the following Table 1.

Table1
Integrated STEM Features and Description

Feature	Description
Open ended problem	Problem that solicits for reflection and thinking Have no definite pattern to the solution Requires investigation, generation of ideas to solve the problem
Real world scenario	Relevant to students in real life so that what is learn is relevant to what the student will encounter in their everyday life
questioning	Question prompts should guide the activities in all units of instruction Questions prompt should be open ended; what do you think, how, why, how does, compare which are thought provoking question that will students develop relevant skills like critical and creative thinking skills
Active engagement	Hands-on activities; physical exploration of materials and experimentation Minds-on activities; engaging the learners higher cognitive skills Situate learning in a social context through collaboration in small groups
collaboration	Encourage small group exchange of ideas and discussion through which learners can acquire collaboration and communicative skills
inquiry	Encourage formulation of problems and hypotheses Encourage generation of data and analysis, evaluation and findings
Teacher as facilitator	Drives the learning process through thought provoking question prompts Ensure students adhere to the rules of collaboration

These features will enhance the learner centered learning environment and will engage the students' higher cognitive abilities which lead to the development of 21st century skills such as critical thinking, creative thinking skills, collaboration and communication skills among others.

ISTEMA Phases

The purpose of learning is not the passive reception of knowledge, but to enable active involvement in the learning process and the development of critical thinking, creative and problem solving among learners. The phases of integrated STEM approach offer such scaffolds because all the phases are designed to engage the learners' cognitive abilities. The phases include; engaging problem, generating ideas, application of ideas to design, evaluation and communication of findings. Each instructional unit will go through these phases and is driven by questioning from the facilitator.

Engaging Problem

This phase involves formulating a problem from a scenario presented or defining an open ended problem or both formulating and defining problem which are vital elements of science and engineering practices. The problem should be an open ended problem that does not have definite pattern to arrive at the solution. Precisely, engaging problem involves stating the goal of the problem, establishing the requirement and limitations, analyze the problem into its constituent parts and their relationship and establish the cause and effect of the problem. In this phase the students' collaboration in small groups to solve the problem and in so doing, their curiosity and thinking skills is engaged (Carrio, Larramona, Banos, & Perex, 2011; Odom & Bell, 2011). An example of an open ended question;

A normal cat length is estimated to be around 30 – 45 cm and the weight is between 1 – 3 kilograms (kg). Its fur is black with red spots. A sales representative from the community contacted your group to engineer a unique cat that is pure breed with attractive colour which can be used as a pet and should be smaller than the normal rabbit.

The goal of this phase is to engage the students in minds-on activities in the learning process, question prompts from the facilitator will include; what do you know about the problem, what is expected to learn? What is the goal of the problem? Analyze the problem into its constituent parts. The students take responsibility for their learning.

Generation of Ideas and Information

In this phase the students' will engage in active exploration to generate information and data that are relevant to solving the problem; students propose solution to the problem. This phase involves gathering meaningful information from print and online materials; establishing existing STEM laws and principles that will be applied to solve the problem, perform experiments as the need arises to generate data. Students acquire an understanding of the solution process and collaborate with each other to establish the best idea that will solve the problem. It is reported that student achievement and problem solving is enhanced when students collaborate to generate ideas. The facilitator will ask the students questions to drive the learning process. What are the STEM principles or laws that help solve the problem and why? What are the best ideas? Why do you think those ideas are best?

Here the students generate the STEM principles that will be applied to solve the problem, such as the law of heredity, principles of probability and algebra, conduct Internet search to generate information. Check for simulation clip that is relevant, collaborate in a small group to determine the best idea to be applied.

The focus in this phase is on generating data, testing idea and designing models.

Application of Ideas to Design

In this phase the ideas generated (scientific, mathematical laws, concepts and principles), data collected are analyzed and interpreted to reveal relationship among constructs and form the basis for making explanation by the students in the previous phase are applied to designing the solution. This involves making the representation of features of the solution in the form of diagrams, sketching designs for the initial model which is an important aspect of the engineering design process. This design, sketching is in the form of representation of students' ideas which will be transformed into a 2D or 3D model, this demonstrates how the students are able to integrate concepts and principles among the STEM disciplines.

Students design and subsequent models should reflect evidence such as patterns, measurement to support the sketch and a solution to the problem. Students are expected to develop a breeding model to achieve the goal of solving the problem.

Evaluation

Students evaluate their design prototypes based on the requirement established in engaging the problem.

> *The facilitator asks the following questions to help learners evaluate their design by asking question such as: is the goal of solving the problem achieved? If yes, why? And if no, why not? How can you improve your design? After answering these questions the design of a solution to the problem can be improved.*

This phase offers the students the opportunity to reflect on the entire process and proceed to redesign or improve their design as the need arises.

Communication of Ideas

At this phase the students share their findings in all the phases, highlighted how the problem was defined, especially the goal of solving the problem, the ideas generated and the best idea selected and why it was selected, how the idea was applied to solve the problem. They highlight the connection between the stem disciplines in solving the problem. The findings are communicated using text, diagrams, prototypes and graphics; students defend their findings using evidence. This phase avails the students the occasion to demonstrate the linkage between concepts and principles among STEM disciplines. This phase will enhance their communication skills and deepen their understanding of the subject matter. The summary of the phases and their description is highlighted in Table 2:

Table2
Summary of the Phases and Their Description

ISTEMA Phases	Sub-phases	Task/Description
Engaging Problem	Understanding and defining the Problem	- Formulating the problem and defining it, - Analysing the problem by breaking down the facts into smaller segments (Maloney, 2007), - Establish the cause and effects of the problem - Asking relevant questions to further understand the problem such as why and how - Establishing clients' needs and highlight the constraints of the problem
Generating Ideas /Information	Collaborative exploration and planning	- Formulation of the possible and alternative ways to solve the problem (Bernik & Žnidaršič, 2012) - Gathering meaningful information from print and online materials, consulting experts, - Generate scientific and mathematical concepts and principles that will be applied - Develop a plan and established strategy
Applying idea/Information to design	Sketch and interpret Design	- Application of mathematics and science concepts and principles to design
	Convert design to a prototype	Sketches to illustrate the design - Translate the sketches into a 2D or 3D based on the specification established during defining the problem - Interpret the design
Evaluation	Evaluate the design process and goal of the engineering process	- Students evaluate their design process and prototype based on the specification or goal of the design challenge - Learners' reflect on the entire process.
Communicating the ideas	Share and defend ideas, discoveries, and argumentation	- Students share, their discoveries, ideas and finding to others and their clients in all the phases - This is achieved through graphic, text, diagrams and through a 3D. - Students are involved in argumentation from evidence

Conclusion

The need to prepare this ISTEMA framework which is characterized by questioning, active learning, collaboration, open ended problem solving among others was born out of the fact that it is an innovative approach and teachers may lack knowledge to implement it. This instructional material is not just about 21st century skills such as critical thinking, creative thinking, communication and collaborative skills, but it emphasizes a paradigm shift and re-positioning of instruction from the traditional teacher centered instruction to the learner centred integrated STEM approach to instruction that enhance the transfer of what is learned in the classroom to real life situation. Further research can be done to determine its effect on students' performance and acquisition of relevant skills.

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