Proposed Model for a Streamlined, Cohesive, and Optimized K-12 STEM Curriculum with a Focus on Engineering

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Abstract

This article presents a proposed model for a clear description of K-12 age-possible engineering knowledge content, in terms of the selection of analytic principles and predictive skills for various grades, based on the mastery of mathematics and science pre-requisites, as mandated by national or state performance standards; and a streamlined, cohesive, and optimized K-12 engineering curriculum, in terms of a continuous educational process that starts at kindergarten and/or elementary schools, intensifies at middle schools, differentiates at high schools and streamlines into four-year universities through two-year community colleges, integrating solid mastery of particular analytic skills and generic engineering design processes. This article is based upon a "Vision Paper" that was presented at the International Technology Education Association's 71st Annual Conference held in Louisville, Kentucky under the sponsorship of Dr. John Mativo, from the University of Georgia. It is hoped that many ideas explored in this article could provide answers to the problems in the current practice of K-12 engineering education, as discussed in the authoritative report issued several months later, on September 8, 2009, by the Committee on K-12 Engineering Education established by the National Academy of Engineering and the National Research Council, titled *Engineering in K-12 Education: Understanding the Status and Improving the Prospects,* which included the absence of cohesive K-12 engineering curriculum and the lack of well-developed standards.

Introduction

In the last decade, it has been perceived by scholars and administrators involved with K-12 STEM education as well as concerned business leaders that the shortage of engineering graduates from U.S. colleges must be resolved. In fact, the numbers of engineering degrees awarded over the last 20 years by U. S. universities was quite small. The National Science Foundation Statistics (2008) indicated that, in the years 1985 - 2005, the number of earned bachelor's degrees ranged from approximately 60,000 to 80,000; the number of earned master's degrees ranged from approximately 20,000 to 34,000; and the number of earned doctorate degrees ranged from approximately 3,700 to 6,000. Wicklein (2006, p. 29) indicated that in the United States, "currently, engineering education has close to a 50% attrition rate for students. […] Georgia currently seeks 50% of the engineering workforce from out-of-state sources." In an effort to solve this problem, K-12 schools across the United States have begun to incorporate engineering design into technology education curriculum. Hill (2006) indicated that "initiatives to integrate engineering design within the field of technology education are increasingly evident." Smith (2007, pp. 2-3) affirmed the achievements made so far throughout U.S. high schools by noting, "the integration of engineering design into secondary technology education classes," but also indicated that the "fragmented focus and lack of a clear curriculum framework" had been "detrimental to the potential of the field and have hindered efforts aimed at achieving the stated goals of technological literacy for all students." An authoritative report issued on September 8, 2009, by the Committee on K-12 Engineering Education established by the National Academy of Engineering and the National Research Council, titled Engineering in *K-12 Education: Understanding the Status and Improving the Prospects,* confirmed the existence of similar problems in the current K-12 engineering curriculum. To be more specific, the most serious problems in K-12 engineering education explored in the report by the Committee on K-12 Engineering Education (2009) include (a) absence of cohesive K-12 engineering curriculum ("Engineering design, the central activity of engineering, is predominant in most K-12 curricular and professional development programs. The treatment of key ideas in engineering, many closely related to engineering design, is much more uneven;" pp. 7-8; p. 151); and (b) lack of well developed standards ("the teaching of engineering in elementary and secondary schools is still very much a work in progress . . . no national or state-level assessments of student accomplishment have been developed;" p. 2).

During the International Technology Education Association's 71st Annual

Conference, and under the sponsorship of Dr. John Mativo, from the University of Georgia, this author presented a proposed model for:

- A Clear Description of K-12 Age-Appropriate Engineering Knowledge Content: Selection of K-12 age-appropriate engineering analytic principles and predictive skills for various grade levels should be based on the mastery of mathematics and science (notably physics and chemistry) prerequisites, as mandated by national or state performance standards for previous or same grade levels.

- A Streamlined, Cohesive, and Optimized K-12 Engineering Curriculum: A cohesive and continuous educational process that starts at kindergarten and elementary schools, intensifies at middle schools, differentiates at high schools, and streamlines into four-year universities through two-year community colleges could be a solution to various problems in U. S. engineering education. This principle of streamlining could also apply to various fields of STEM (see Figures 1 and 2). The optimization of K-12 engineering education could be achieved through (a) the integration of particular analytic and predictive principles and skills, with different modes of generic engineering design process, both transferable to collegiate engineering studies and (b) the integration of traditional formula-based analytic computations and physical laboratory experiments with modern digital simulation technology. The proposed curriculum is intended to seamlessly link K-12 engineering and technology curricula to university engineering programs, by making engineering knowledge content learned at K-12 schools transferable to engineering courses taught at the university level; this is the "missing E" (engineering) that has been neglected by existing models of K-12 STEM curricula.

This proposed model might contribute to the solution of the problems described in the report by the Committee on K-12 Engineering Education (2009).

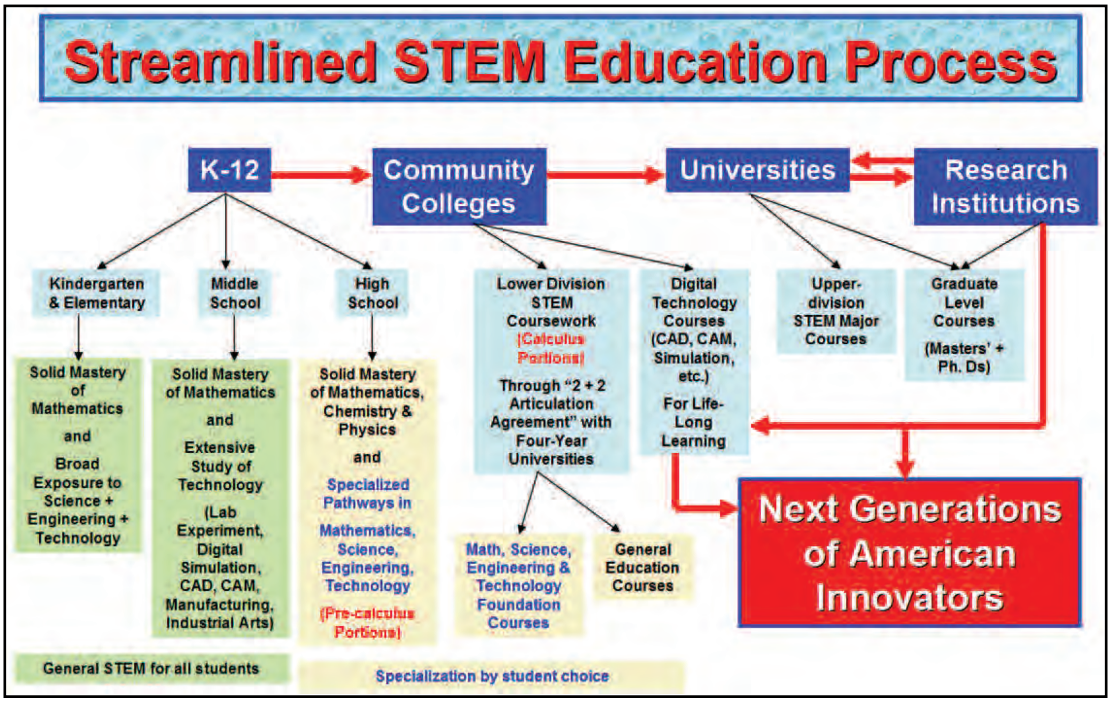

Figure 1. A streamlined vision for a life-long STEM education.

Proposed Model for a Clear Description of K-12 Age-Appropriate Engineering Knowledge Content

The key to understanding how to scientifically, rationally, and effectively infuse engineering analytic content knowledge and the design process into K-12 curriculum can be related to the understanding of the following four basic types of relations:

(1) Relations among mathematics, science, engineering, and technology: Mathematics provides computational tools for the predictive analysis in sciences, engineering, and technology; it is the primary gatekeeper for the inclusion

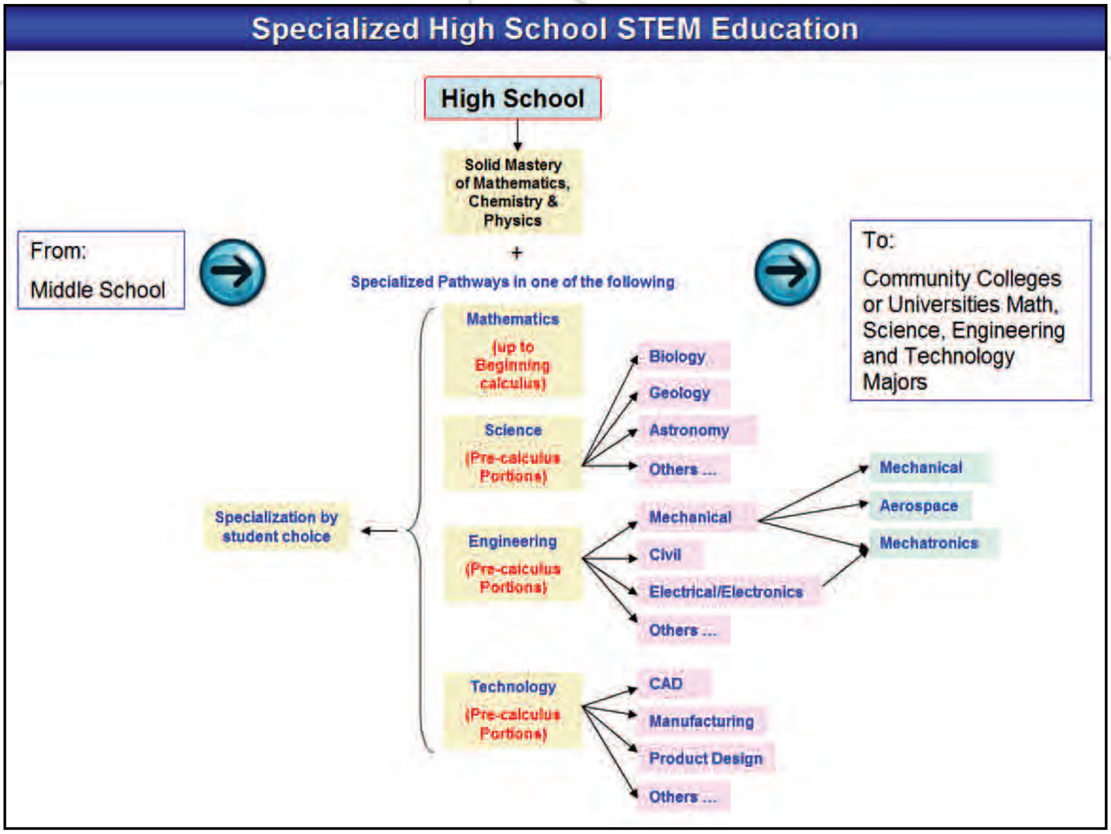

Figure 2. A streamlined model for STEM education.

or noninclusion of any science, engineering, or technology topic into any course taught at any grade level. Sciences (physics, chemistry, biology, etc.) are concerned with discovery and delivery of knowledge, and they form the foundation for engineering and technology; additionally, sciences (notably physics and chemistry) constitute the secondary gatekeeping determinants. Engineers apply knowledge gained through the scientific process in the creative design of products and systems to be used in solving everyday problems, and they are the vital link in the STEM system that transforms "pure" knowledge into usable and financially profitable assets (products and systems), through the process of innovation. Technology is the skills of applying, maintaining, and arranging products and systems in the solution of daily problems. Based on this understanding, the selection of engineering topics for any grade level must be based on the prior mastery of prerequisite principles and skills in mathematics and science courses.

(2) Relations between specific engineering analytic knowledge content and the generic engineering design process: Mastery of a sufficient amount of specific analytic knowledge content (principles, concepts, computational skills using formulas or simulation software, as well as experimental and research methods) constitutes the foundation for meaningful engineering design; in contrast, engineering design gives students an opportunity to synthesize knowledge and skills gained from various branches of engineering into workable solutions that help create and maintain usable products and systems. Based on this understanding, the inclusion of engineering as a meaningful K-12 subject must be based on an appropriate balance between instruction of specific engineering analytic knowledge content and the inculcation of the ability of using engineering design processes.

(3) Relations between different modes of design and different stages of K-12 students' cognitive developmental level: Design processes could include different modes.

- Creative and Conceptual Design: Examples of this mode include conceptual imagination, ideation for simple product and tools (e.g., everyday items, such as shopping bags, benches, chairs, tables). Kindergarten and elementary school students are good at wild imagination with little training, but at this age they are just beginning to learn basic mathematics and sciences; thus, this mode could be used in Grades K-5.

- Technology Education Design: This mode of design is based on "trial-and-error" or "hypothesis-and-testing" experiments; and it is an important method of scientific inquiry. An example of this mode could be the design, fabrication, and testing of composite materials, based on a rational hypothesis and its proof or disproof through experiments. This mode could be used in Grades 6-8.

- Analytic Reduction: This mode is good for solving well-structured, simple, and usually closed-ended engineering design problems (e.g., designing a gear set that changes speed and direction of rotational motions) that are focused on scientific and technological issues. It is suitable for stand-alone engineering foundation or specialty courses that deal with particular sets of knowledge content. This mode could be used in Grades 9-11.

- Systems Thinking: This mode of design is good for solving ill-structured, open-ended, and complex engineering design problems, which involve not only many branches of science and engineering, but also social studies (culture and economics), ecology and arts. It generally could lead to multiple results that satisfy the original design requirements. This is the most frequently used mode in real-world engineering design practice. Examples of this mode include senior-year design projects in any typical university undergraduate engineering program. This mode would be most suitable for Grade 12 or graduation year "capstone" design courses, and it could be used for extracurricular interdisciplinary design projects throughout Grades K-12.

Engaging K-12 students in the design process is feasible. Previous research conducted by Fleer (2000) and funded by the University of Canberra and the Curriculum Corporation of Australia for the development of a technology curriculum concluded that children as young as 3 to 5 years of age can engage in oral and visual planning as part of the process of making things from materials; their planning involved the use of lists and designs of what they intended to make. Claxton, Pannells, and Rhoads (2005) indicated that the level of developmental maturity occurred around 5 to 6 years of age; that a creative peak occurred at 10 to 11 years old; and that "after age 12, a gradual but steady rise in creativity occurred through the rest of adolescence until a second peak was reached around 16 years of age" (p. 328).

(4) Relations between kindergarten/elementary education and secondary education: Throughout the Grades K-6, students barely learn the basics of STEM, English language, and other mandated subjects; they have a very limited set of mathematics skills to carry out engineering analysis and prediction-related computations; thus, an integrative STEM approach in general science courses, with broad exposure to a variety of science, engineering, and technology subjects, would be very age-appropriate. At the secondary level, students either have mastered or are in the process of mastering more in-depth and specialized mathematics skills (algebra, geometry, trigonometry), and they have mastered basic scientific principles that are needed for understanding engineering analytic principles; thus, more extensive engineering studies could be implemented; here, depth and specialty should be emphasized.

Method for the Selection of K-12 Age-Appropriate Analytic Principles and Skills

Up to this date, "hard-core" engineering content from various subjects, such as statics, dynamics, and fluid mechanics, are generally not systematically taught until students enroll in university undergraduate courses; however, textbooks used in these courses could be analyzed to determine the mathematics and science (notably physics and chemistry) prerequisites for various topics covered therein. Topics whose prerequisites are covered at various K-12 grade levels could be selected for pedagogic experiments at higher grade levels, to determine their age-appropriateness. This author's research on high school age-appropriate statics and fluid mechanics topics, during Spring 2009, at the University of Georgia, incorporated the following steps:

(1) Select textbooks and instructor solution manuals that are among the most popular for undergraduate engineering statics and fluid mechanics courses;

(2) Read carefully every paragraph in the body text to find and record the prerequisite science knowledge content needed for each topic (notably physics and chemistry);

(3) Find the relevant computational formulas to determine and record the mathematics skills needed; and

(4) Compare the recorded data with the mandates of the Performance Standards for Mathematics and Sciences of the Department of Education of a selected state, to determine the grade level for the inclusion of the topic.

This previous research indicated that, using the mandates of the Performance Standards for Mathematics and Sciences of one of the "low-performing" states in the United States, around 50% of all topics in the textbooks used in undergraduate statics and fluid mechanics courses are based on precalculus mathematics skills and on scientific principles that are covered prior to 9th grade, and therefore, could be taught to 9th Grade high school students. For other foundation engineering courses common to all undergraduate programs, such as dynamics, strength of materials and material science, heat transfer, thermodynamics, engineering economics, and aerodynamics, the percentage figure ranges from 30% to 50% based on this author's rough estimates using similar standards.

Even though high school students could learn engineering topics, this does not automatically mean that they would have enough energy to proceed. Due to many factors, K-12 schedules are crowded with many mandated subjects; and the academic resources for implementing engineering curriculum are rather limited. Thus, realistically only the most important engineering analytic content knowledge can be attempted to be infused in the curriculum. Expert opinions of the relative importance of various topics can be collected, possibly through a five-point Likert scale, four-round Delphi survey. This survey could be used to determine the relative importance of various engineering analytic principles and computational skills for inclusion into a potentially viable K-12 engineering curriculum and eventually to establish a set of national or state K-12 engineering performance standards.

Proposed Model for a Streamlined, Cohesive, and Optimized K-12 Engineering Curriculum

Based on the above mechanism for the development of a clear description of K-12 age-appropriate engineering knowledge content, in this article the author proposes a new model for a streamlined, cohesive, logical, and optimized K-12 Engineering Curriculum, which could also be used as a general model for STEM, including mathematics and sciences (Figures 1 and 2). This new model could provide a workable framework for organizing and sequencing the essential knowledge and skills to be developed through K-12 engineering education in a rigorous or systematic way, making the future K-12 Engineering curriculum optimally connected to college-level engineering programs and to real world practice, and eventually lead to the establishment of formal national and state learning standards or guidelines on K-12 Engineering Education.

The Proposed Model would include two components: a Regular Curriculum (Table 1) for all students enrolled in K-12 Engineering Curriculum or "Career Pathways," and an Extracurricular Enrichment Program for selected groups of students.

First Component - Regular Curriculum

Lewis (2007) indicated that, "to become more entrenched in schools, engineering education will have to take on the features of a school subject and argued in terms of what is good for children" (p. 846). In addition, Lewis (2007) discussed the need to (a) establish a "codified body of knowledge that can be ordered and articulated across the grades" with focused attempt to systematize the state of the art in engineering in a way that is translatable in schools (instead of short term efforts focused on a particular topic or unit) and (b) make engineering education a coherent system with the creation of content standards for the subject area, in line with science and technology education (pp. 846-848).

As shown in Table 1, the Regular Curriculum is designed for all students who are interested in STEM Career Pathways and could be adequately trained in basic mathematics skills; it is aimed at implementing engineering design process step-by-step, progressing from simple to complex, from easy to difficult, from broad to deep, from generic to special, in an incremental, logical, systematic, and cohesive sequence. This is based on age-appropriateness, with a deep respect for time-proven traditional pedagogy while incorporating the positive achievements of the recent decade in instructional technology, especially in terms of digital modeling and simulation technology. This curriculum is divided into several stages, each corresponding to the infusion of engineering

Table 1. Regular K-12 Engineering Curriculum Flow Chart

Grades K-5 (Kindergarten & Elementary School) → For all students	**Grades 6-8 (Middle School)** → For all students, especially the STEM-oriented ones	**Grades 9-11 (High School)** → For all Engineering Pathway students	**Grade 12 (High School Graduation Year)** → For all Engineering Pathway students
Knowledge Content (Course Works)			
STEM Courses (2 courses; throughout Grades K-5): 1st Course (Grades K-5) - Mathematics. 2nd Course (Grades K-5) - Integrated Science, Engineering and Technology: • General Principles of Science, Engineering and Technology; • Diverse Topics in Science, Engineering and Technology; • Ecologically Sustainable Application of Science, Engineering and Technology. • Careers & Ethics in Science, Engineering and Technology. →	Mathematics & Science (2 courses; throughout Grades 6-8). Technology (8 Subjects organized into 4 Full Year Courses; 1 Course per Grade/Year): 1st Course (Grade 6) - Product Design & Manufacturing: • Engineering Drafting, Solid Modeling & Product Design; • Manufacturing Systems. 2nd Course (Grade 7, an extension to Grade 6 Science Course) - Humans & Environment: • Power & Energy; • Construction Systems. 3rd Course (Grade 8) - Technology Aesthetics & Ergonomics: • Digital Graphics Design & Product Aesthetics; • Ergonomics, Safety & Appropriate Technology Development. 4th Course (Grade 8, to be taught as a part of Science Course) - Electronics & Control Technology: • Electrical Circuitry Design, Component Selection & Digital Simulation; • Robotics Assembly & Programming. →	Mathematics & Sciences (2 courses; throughout Grades 9-11. For Sciences, Physics and Chemistry are mandatory). Engineering Foundation (Several Subjects organized into 3 Courses; 1 Course per Semester): 1st Course (Grade 9, 1st Semester) - Engineering Mechanics I: • Statics & Dynamics; 2nd Course (Grade 9, 2nd Semester) - Engineering Mechanics II: • Fluid Mechanics & Aerodynamics; • Heat Transfer & Thermodynamics. 3rd Course (Grade 10, 1st Semester) - Engineering Materials: • Strength of Materials; • Materials Properties, Treatment & Selection. Engineering Pathway (3 courses; 1/semester; 2nd Semester of Grade 10, 1st and 2nd Semester of Grade 11). → Note: For non-Engineering Pathways (Science, Technology and mathematics), the Foundation and Pathway courses would be different.	Design "Capstone" (2 Courses at Grades 12). 1st Course (Grade 12, 1st Semester) - Engineering Design Capstone I: • Mini Lesson: Engineering Economics, and other topics relevant to the design project; • Design activities (teamwork). 2nd Course (Grade 12, 2nd Semester) - Engineering Design Capstone II: • Design activities (teamwork). • Prototyping activities (teamwork). Note: For non-Engineering Pathways (Science, Technology and mathematics), the Design "Capstone" courses would be changed to Research or Manufacturing "Capstone."
Mode of Design Process			
Creative, Conceptual and light analytic (assignments). →	Engineering & Technology Experiment (assignments). →	Analytic Reduction" for "Well-structured problems ("Mini Capstone" or final design or research project for each course) →	Ill-structured and Systems Thinking" ("Capstone" graduation project)

design into a period of K-12 education: (a) kindergarten and elementary schools; (b) middle schools; (c) high schools; and (d) graduation year.

At Grades K-5 (kindergarten to elementary schools): All students would be introduced to science, engineering, and technology, while they built a solid foundation in mathematics.

Students would be given an opportunity to: (a) have a broad exposure to diverse aspects of science, engineering and technology (the "breadth"); (b) foster ability of creative imagination (the "wild"); and (c) foster a systemic and holistic view of technological systems as interactive and interconnected. Students would master similar knowledge content that is traditionally required of college engineering and technology students in the following courses: Introduction to Science, Engineering and Technology; Engineering Ethics; and Appropriate Engineering and Technology. This stage would be similar to what many of U.S. K-12 schools have practiced during the past decade. Minimal modifications would be made regarding infusing age-appropriate engineering knowledge content through contextual, hands-on, and creative design activities.

At Grades 6-8 (middle schools): Courses included in this stage should be made available to all students and taken by all STEM-oriented students. During this stage, all students would consolidate their mathematics and science foundation and explore the basics of traditional and modern technology with more specialized and stand-alone courses. Students would master the fundamentals of modern technology that are associated with engineering (e.g., CAD and 3D modeling, traditional and CNC manufacturing process, and others). This coursework would prepare them for a lifelong career related to STEM. For non-STEM-oriented students, technology courses included in this part of the Proposed Model could still help them to gain practical skills with lifelong benefits. The mathematics and science portions of this part of the Proposed Model would still be similar to what most of U.S. schools have practiced in the past, except that the content knowledge would be more specialized and intensive, including some relevant engineering topics, either as "word problems" or as mini research projects. In addition, specialized and intensive engineering-related technology courses would be offered.

At Grades 9-11 (high schools): Selective courses included in this stage should be taken by students enrolled in separate STEM Career Pathways; as shown in Figure 2, these Career Pathways could be any branches of science (biology, chemistry, physics, etc.), technology (CAD, manufacturing, product design, etc.), engineering (mechanical, civil, electrical and electronics, etc.), depending on changing national and local needs. During this stage, students would be branched out to different STEM "Career Pathways" of their choice, take a sequence of precalculus based, well-connected, and specialized courses. The specialized STEM "Career Pathways" would directly streamline students into relevant STEM majors at colleges or universities through cross-institutional transfer and/or articulation agreements, which might include dual high school and college credits (for technology courses such as engineering drafting and CAD/CAM) and the High School Certificate Examination in a particular area of STEM, for the completion of certain courses (such as Introduction to Science, Engineering, and Technology, Engineering Ethics, Appropriate Technology, etc.) or their precalculus portions. In the future, special examinations modeled after Fundamentals of Engineering (FE) could be designed to test the abilities of high school graduates to solve precalculus-level engineering problems. For students who pass these examinations, special accommodations could be granted (e.g., they would still be enrolled in undergraduate engineering courses to continue studying relevant topics beyond the precalculus portions they have learned at high schools, but they could be exempt from specific homework and quizzes related to precalculus portions, allowing them to devote their time to calculus-based course materials and to engineering design and research projects.

At Grade 12 (high school graduation year): The mathematics and science portions of this part of the Proposed Model would still be similar to what most U.S. schools have practiced during the past decade, leading to graduation from high school and entry into college education. In the last year of K-12 education, students enrolled in STEM "Career Pathways" would spend two semesters in a research or design "Capstone" project to demonstrate their ability to synthesize the knowledge content from various courses taken previously and to solve an open-ended real-world problem with reasonable complexity, in a "System Thinking" mode. This project could constitute the masterpiece of the students' academic portfolio. The instructors would advise, guide, and evaluate students, and they would teach additional topics relevant to the "Capstone" projects.

Core engineering concepts "go beyond tool skills… and beyond the digital skills that have captured the interest of the profession over the past two decades. Tools will change but even more important is the cognitive content and intellectual processes fundamental to effective technological problem solving and literacy" (Sanders, 2008, p. 6). The idea of a precalculus but "hard-core" high school engineering curriculum, the centerpiece of the Proposed Model is feasible. Most basic scientific principles and analytic skills related to engineering design that practical engineers work with on a regular basis are based on precalculus mathematics (trigonometry, algebra, geometry, and functions) with some needs for beginning calculus (integration and differentiation) and substantial needs for linear algebra. Traditionally, "hard-core" engineering topics are taught in lower division courses of undergraduate engineering programs. However, because precalculus mathematic is offered in most U.S. high schools, there is a reasonable possibility that some portions of traditional college-level engineering content knowledge could be downloaded to high school students, in order to streamline their pathway to engineering careers. Therefore, it is feasible to develop and implement a high school engineering curriculum that could be seamlessly connected to college engineering programs.

The Proposed Model for K-12 Engineering Curriculum is designed to solve the problem of the chronic shortage of engineering graduates in the United States, by offering K-12 students a better preparation for college-level engineering majors; it can selectively teach high school students appropriate engineering knowledge content (the "precalculus portions"), which up to this point, remain the domain of university undergraduate engineering programs. Adopting this model could allow high school graduates from engineering and technology curricula to have mastered a sufficient amount of engineering analytical skills that are transferable to undergraduate engineering courses, so they could spend a few weeks reviewing the "precalculus portions" of the course materials and then concentrate on the more difficult calculus-based portions. This would (a) give academically challenged high school students a better chance to pursue engineering studies as "early birds" and thus increase the enrollment of domestic students in undergraduate engineering majors; (b) give U.S. undergraduate engineering students the same "early bird" advantage over those in many other countries; and (c) give college engineering professors a better way to manage course schedules. The students would be more adequately prepared to handle, the coursework, and this should improve the quality of undergraduate engineering education and reduce the dropout rate.

Second Component - Extracurricular Enrichment Program

The Extracurricular Enrichment Program could be operated in two formats.

Table 2. Commonly Shared Undergraduate Lower-Division Engineering Foundation Courses Among Various Engineering Programs at the University of Georgia, Based on Data from Undergraduate Engineering Program Handouts (Available from Room 120, Driftmier Engineering Center, Athens, Georgia 30602).

University of Georgia Engineering Program	University of Georgia Engineering Foundation Courses								
	ENGR 1120 Graphics & Design	ENGR 2120 Statics	ENGR 2130 Dynamics	ENGR 2140 Strength of Materials	ENGR Fluid Mechanics	ENGR 3140 Thermo-dynamics	ENGR 3150 Heat Transfer	ENGR 2920 Electrical Circuits	ENGR 2110 Engineering Decision Making
B.S. in Agricultural Engineering									
Electrical & Electronic Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mechanical Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓
Natural Resource Management	✓	✓	✓	✓	✓	✓	✓	✓	✓
Structural Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓
Process Operations	✓	✓	✓	✓	✓	✓	✓	✓	✓
B. S. in Biological Engineering									
Environmental Area of Emphasis	✓	✓		✓	✓	✓	✓	✓	✓
Biochemical Area of Emphasis	✓	✓		✓	✓	✓	✓	✓	✓
Biomedical Area of Emphasis • Biomechanics Track • Instrmentation Track	✓	✓		✓	✓	✓	✓	✓	✓

Infusing Engineering Topics Into K-12 Mathematics and Science Courses.

In addition to teaching engineering analysis and design through special Career Pathway courses, suitable engineering content could be incorporated into regular middle school and high school mathematics, chemistry, and physics courses, as extra teaching materials, word problems, and simple design projects. For example, in a geometry course, the engineering application of the triangular shapes could be explained to students, such as a triangle is "indestructible," unless the side lengths are changed, the shape would stay intact. In addition, triangular members are widely used in structural design; bridge design projects could be incorporated, with learning materials from the Internet, to study the subject of force equilibrium, to simulate bridge design with West Point Bridge Design software (http://bridgecontest.usma.edu/), and to build a scale model. Moreover, because triangles have one straight edge opposite a sharp corner, they can accommodate different shapes in three-dimensional space and are used in the development of irregular or curved surfaces; thus, some topics of engineering sheet-metal design could be taught, giving the students an opportunity to design a transition piece, as shown in Figure 3. In a chemistry course, subjects of material selections could be incorporated. Other appropriate engineering topics could be identified by engineering and technology faculty and graduate students using well-established criteria, and gradually added to regular K-12 mathematics, physics, and chemistry courses as extra learning materials, through a process of pilot study or other mechanism of pedagogic experiment. This approach is simple, easy to implement, and virtually risk-free. It would not likely cause any disturbance to routine K-12 mathematics and science instruction.

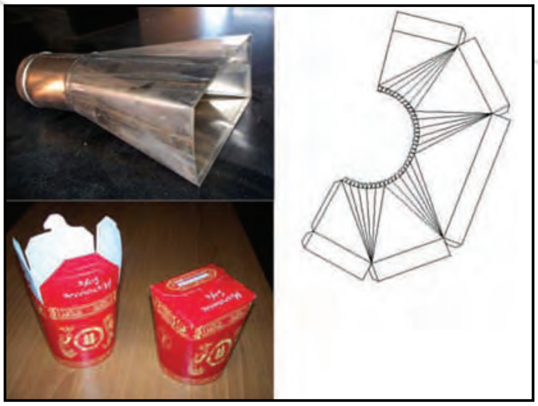

Figure 3. Examples of circle-to-square transition pieces (sheet-metal connector and restaurant take-home food container).

Interdisciplinary Design Projects

Engineering design projects involving knowledge and skills from a variety of subjects could be implemented through after-school club activities or through training sessions during summer vacations. Such enrichment programs could provide students enrolled in STEM pathways an opportunity to (a) review previously learned scientific principles and skills while learning new ones that are relevant to the design projects; (b) integrate principles and skills from various STEM subjects and non-STEM subjects (e.g., social study, arts.), into practical design solutions; and (c) foster the ability to combine both "analytic reduction" and "system thinking" modes of the engineering design process, for solving real-world problems in a real-world manner. Mativo and Sirinterlikci (2005) developed an "animatronics" design project for student (Grades 7-12) It included an open-ended and creative project for the design of lifelike entertainment robots or dynamic and interactive animated toys with a mechatronic blob, penguin, robotic trash can, and a human-monster hybrid. These could cruise, wave swords, flip wings, and light eyes, in fun and creative team environments. They combined analytic and design skills from the following different but interconnected fields: (a) mechanical engineering (material and manufacturing process selection, including metals, ceramics, plastics and composites; mechanism design and assembly of levers and cranks, etc.); (b) electronics (actuators, sensors, controls); (c) microcontrollers' structure and programming; (d) emerging technologies, such as muscle wires, air muscles, micro- and nanocontrollers; (e) two- and three-dimensional art (costuming from fabrics to rubber Latex, and modeling), and (f) industrial product design. The implementation of this project indicated that students' academic performance improved through interdisciplinary engineering design activities. See figure 4. In summary, in addition to a Regular Curriculum, an Extracurricular Enrichment Program would be an effective supplement to help consolidate students' mastery of fundamental knowledge and creative design ability.

Potentially Realistic Students' Learning Outcomes

For students enrolled in K-12 Engineering Curriculum, when they graduate from high

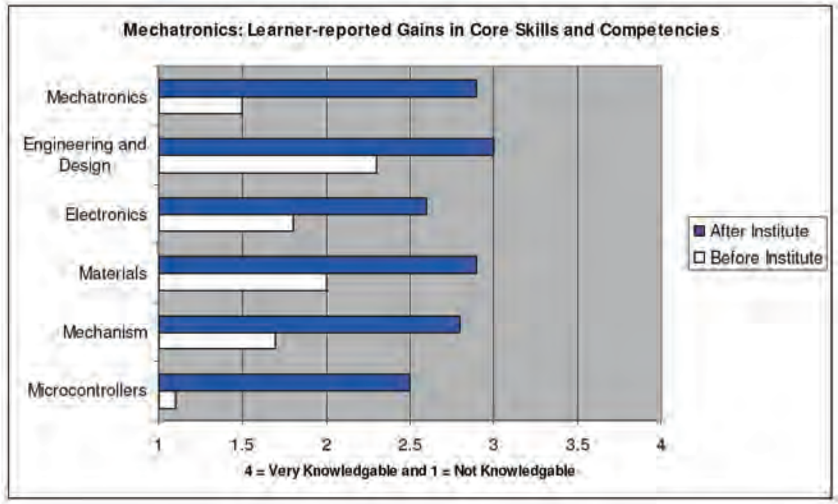

Figure 4. Sirinterlikci and Mativo's Animatronics project helped students improve STEM learning through inclusion of engineering design (Mativo & Sirinterlikci, 2005a).

schools, they could realistically be expected to have (a) built a solid foundation in precalculus mathematics and sciences; (b) learned the basics of engineering-related industrial arts and digital modeling and simulation technology; (c) mastered a sufficiently large portion of precalculus-based engineering analytic principles and predictive computational skills; and (d) become familiar with various modes of the engineering design process. These potentially realistic learning outcomes could give these students the freedom to choose any of the following:

(1) Enrollment in college engineering programs as full-time students with a solid mastery of the precalculus-based portions of foundation courses as well as practical engineering design and research skills; or

(2) Entry into job market as technical employees, such as CAD drafters with some entry-level ability to design simple products (e.g., furniture, tools, toys with electronic devices and kitchen appliances with simple circuitry and mechanical components), while enrolling as part-time students in engineering and technology programs, including two-year technical certificate or four-year bachelor of science degrees; or

(3) Enrollment in non-engineering university undergraduate majors (e.g., science and mathematics) with useful abilities and skills for lifelong career enhancement; for example, a future scientist or mathematicians would be able to design and prototype devices to facilitate experiments or teaching.

Notice that the aforementioned choices are simply convenient suggestions, and by no means do they constitute any intended idea about "academic tracking." If the Proposed Model were adequately implemented, then all students enrolled in K-12 STEM Career Pathways (all types of achievers), could be better prepared for a science or engineering major at the college level. Therefore, the Proposed Model should be considered as an egalitarian (although upward mobile and flexible) model that promotes equal preparation for college engineering majors from an academic perspective; it would be up to the students to choose their Career Pathways. The ultimate purpose of the Proposed Model is to educate new generations of innovative engineers or professionals in other fields. This could be accomplished by launching K-12 students early into engineering studies, so that they could foster analytic and innovative capacities early in life. Modern engineering education is more complicated than ever before, due to the explosion of new knowledge and technologies, especially those related to digital modeling and simulation. In addition, traditional engineering education has been somehow challenging to students due to heavy requirements on calculus-based mathematics, physics, and engineering course work. Therefore, engaging students early in the Engineering Career Pathways would make sense. It is not this author's expectation for K-12 students to become instantaneous robotic designers or spacecraft engineers (although the highest academic achievers among them should be given adequate preparation for careers of vital national interests). This is generally beyond their cognitive maturity (except in some high-achieving communities where economic and educational conditions might magically allow this to happen); instead, we should aim at matching K-12 engineering and technology education with the cognitive maturity level of average K-12 students. Taking the Mechanical Engineering Career Pathway as an example, they could be expected to graduate from the program with some creative abilities and analytic skills to design and prototype everyday products or systems, with simple mechanical and electronic components (either of their own design or from out-of-shelf selection), which are professionally ready for production or installation; and these could include toys, utensils, furniture, clothing, and fastening devices. This might be doable for average high school graduates. But they should not be expected to design robots except the very simple ones using out-of-shelf components. Expecting too much from K-12 students without a reasonable chance to succeed would not be the best way to prepare them for a brilliant engineering career. This line of thinking is compatible with the "everyday technology" idea of broadly defining "the term technology to include the artifacts of everyday life as well as environments and systems," of "focusing on the technologies of everyday life," and of allowing children to "solve problems of real significance in their lives," which have been explained by Benenson (2001, pp. 730-732), in presenting his 10-year long City Technology project.

Potential Benefits of the Proposed Model

The Proposed Model's most important potential benefit is the symbiotic integration of specific engineering analytic knowledge content with various modes of generic engineering design process, for it is self-evident that without teaching K-12 students particular age-appropriate engineering analytic and predictive knowledge content, they could not build a solid foundation of knowledge and skills for further study of engineering at college level. Also, without giving such students opportunities to practice age-appropriate engineering design, they would not be able to synthesize various sets of knowledge and skills into practical solutions of real-world problems and to form appropriate engineering thinking habits. The aim of infusing engineering analytic and predictive principles and computational skills into a potentially viable K-12 engineering curriculum is NOT to make students instruments of computations, or to encourage rote memorization of engineering analytic principles and computational formulas, or their applications in solving a few simple homework problems in the purely "Analytic Reduction" model (although all of the above are necessary tasks); however the aim is to foster the real ability of solving real-world problems, which involve integration of engineering analytic principles. It also involves, of course, computational formulas, from various subjects, as well as knowledge from art, social and ecological studies, and others, into a "system thinking" model of holistic problem solving. This focus on solving problems could foster students' real ability in innovative engineering design that is based on solid mastery of necessary analytic tools. This would allow them to use the generic engineering design approach to create real-world quality products and systems, which are appropriate to their age, technically feasible, and socially and ecologically appropriate.

Conclusions

This article has provided a workable framework for defining K-12 age-appropriate engineering knowledge content and an outline for a new paradigm for a streamlined, cohesive, and optimized lifelong STEM education in the United States, with a focus in engineering. For additional details of the Proposed Model, please contact the author at edwardnlocke@yahoo.com. In order to improve K-12 engineering education, the following recommendations and plans are hereby presented for consideration, support, and implementation:

1. <u>Organization:</u> Establish a network of stakeholders, to include, (a) government officers in charge of K-12 STEM education at Federal and state levels, (b) leaders of National Centers for Engineering and Technology Education and other institutions of authority in K-12 engineering education, (c) scholars in the fields of engineering and technology education from universities and research institutions, (d) school district administrators and engineering and technology teachers, (e) representatives from the business community and nonprofit organizations, and (f) university engineering students. This network could offer stakeholders an opportunity

to discuss specific policies, measures, actions to be taken for the solution of problems listed in the report by the Committee on K-12 Engineering Education (2009). It could also offer them criticism and advice regarding the improvement of the model of the K-12 Engineering Curriculum proposed in this article, so that it could eventually become a collective proposal accepted by all or most of the stakeholders.

2. Research: Continue research on defining K-12 age-appropriate engineering knowledge content from the following subjects: dynamics, strength of materials, material science, heat transfer, thermodynamics, engineering economics, aerodynamics, and mechanism design; this will lead to the eventual publication of *The Handbook of Proposed Engineering Topics with Analytic Principles, Computational Formulas and Units for K-12 Schools (with Reviews for Mathematics and Sciences).* This research constitutes the most important prerequisite for the implementation of the K-12 Engineering Curriculum proposed in this article. It would be an important reference for the development of K-12 engineering teaching materials and the improvement of K-12 engineering and technology teacher training programs.

3. Pilot study: K-12 schools (especially high schools, including charter schools) could be found to conduct pilot pedagogic experiments to determine the age-appropriateness of all K-12 feasible engineering analytic knowledge content to be identified in the above-mentioned *Handbook* to be published in the near future.

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