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Engineering design skills coverage in K-12 engineering program curriculum materials in the USA

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ABSTRACT

The current *K-12 Science Education* framework and *Next Generation Science Standards* (NGSS) in the United States emphasise the integration of engineering design in science instruction to promote scientific literacy and engineering design skills among students. As such, many engineering education programmes have developed curriculum materials that are being used in K-12 settings. However, little is known about the nature and extent to which engineering design skills outlined in NGSS are addressed in these K-12 engineering education programme curriculum materials. We analysed nine K-12 engineering education programmes for the nature and extent of engineering design skills coverage. Results show that developing possible solutions and actual designing of prototypes were the highly covered engineering design skills; specification of clear goals, criteria, and constraints received medium coverage; defining and identifying an engineering problem; optimising the design solution; and demonstrating how a prototype works, and making iterations to improve designs were lowly covered. These trends were similar across grade levels and across discipline-specific curriculum materials. These results have implications on engineering design-integrated science teaching and learning in K-12 settings.

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Introduction

In today's global economy, a workforce trained in science, technology, engineering, and mathematics (STEM) is recognised as a primary driver of economic growth of every nation (National Academy of Engineering [NAE], 2014; National Research Council [NRC], 2012). As such, many countries are investing more in K-12 STEM education (Rogers, Wendell, & Foster, 2010). For example, in the U.S., *The New Framework for K-12 Science Education* (NRC, 2012) and the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) accentuate the integration of engineering design in K-12 science instruction. These new science education reforms have fostered a connection between engineering and science education to help better prepare students and society to meet current and future challenges of modern and technological society (NAE, 2014; NRC, 2012). In the U.S. states that have adopted NGSS science teachers are required to teach engineering design and science content knowledge to their students. In particular,

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teachers are expected to engage students in the following engineering design skills that are outlined in NGSS (NGSS Lead States, 2013): (a) defining and delimiting engineering problems so that they can understand the problem as well as the criteria and constraints in which the design solution must function well; (b) developing design solutions which can aid students in generating ideas to inform the development of design solutions; (c) optimising the design solution so as to determine the best solution from a myriad of competing criteria; engaging students in design activities and testing them; and (d) making revisions or iterations to improve the design solutions. These engineering design skills complement the science practices such as asking scientifically oriented questions, planning and conducting investigations, analysing and interpreting data, constructing explanations, giving priority to evidence, and communicating and justifying explanations (NRC, 2012). Engaging students in engineering design as a learning context in science enhance their understanding of how scientific knowledge can inform the design of knowledge-based artefacts, and the link between science and engineering (Kimmel & Rockland, 2002). Furthermore, engineering design can help students develop a meaningful understanding of science concepts and how those concepts can be used to solve engineering problems facing society (Bamberger & Cahill, 2013). Engineering design as a learning context is critical to the application of science concepts when defining engineering problems and when determining possible solutions to the problems (Sadler, Coyle, & Schwartz, 2000).

In response to the inclusion of engineering design in *The New Framework for K-12 science Education* and NGSS, many engineering education programmes, funded by federal government funding agencies, foundations, and private companies, have developed engineering design curricular materials for K-12 science classrooms such as Engineering by Design; Engineering is Elementary (EiE); Infinity Project; Project Lead the Way; City Technology (CT); Learning by Design (LbD); Gateway to Technology (GT); Engineering by Design (EbD); Engineering for Today's Intermediate School (ETIS); World In Motion (AWIM=A); Teach Engineering (TE); and Principles of Engineering (PoE). All these engineering design curriculum materials are being used in several science classrooms and teacher education programmes across the U.S.

Despite the existence of these engineering design curriculum materials, little is known about the nature and extent to which these materials address engineering design skills outlined in *The New Framework* for *K-12 Science Education* and NGSS. To date, most studies on engineering design in K-12 science classrooms have mainly focused on students' engagement in science through design problems (Crismond, 2001; Kolodner et al., 2003; Mehalik, Doppelt, & Schunn, 2008; Sadler et al., 2000); students' engagement in design process (Roth, 1996; Penner, Giles, Lehrer, & Schauble, 1997, 1998); and students' designing abilities (Cunningham, Lachapelle, & Lindgren-Steicher, 2005; Resnick, Berg, & Eisenberg, 2000). In general, these studies concluded that the use of engineering design as a context for science instruction produced promising findings in students' learning gains (e.g. Apedoe, Reynolds, Ellefson, & Schunn, 2008; Kolodner et al., 2003; Wendell & Lee, 2010).

Other studies have examined the extent to which engineering design skills are addressed in the articles published in engineering education journals (e.g. Gómez Puente, van Eijck, & Jochems, 2011; Mehalik & Schunn, 2006). Mehalik et al. conducted a meta-analysis of journal articles of empirical studies of the design process and found that *exploring/defining the problem*, *using iterations*, and *exploring alternatives/designing* *possible solutions* received a high degree of frequency, and were also categorised to be significant for good design; *explore graphic representation, redefine and explore scope of constraints, validate assumptions and constraints, examine existing designs, and explore user perspectives* received a moderate frequency and considered significant for good design; *building normative models (optimisation)* was reported with a moderate frequency coverage, but considered as may be significant for good design. Design elements that were reported with a low frequency were *explore engineering facts, explore issues of measurement, conduct failure analysis,* and *encourage reflection on process.* Similarly, Gómez Puente et al. (2011) characterised engineering design-based learning using 50 empirical studies and compared across different engineering disciplines, educational levels, authentic, and artificial design activities. With respect to engineering disciplines, the design element *explore problem representation* and *explore issues of measurement* were reported with a lower frequency in mechanical engineering in comparison with the other domains. However, the design element *build normative model* did not differ substantially between all domains. With regard to the level of learners expertise, design skills *explore alternatives, redefine constraints, explore scope of constraints, explore issues of measurement, and encourage reflection on process* were reported more frequently in undergraduate programmes. To the contrary, design skills such as 'Examine existing designs', 'Explore problem representation', 'Explore user perspective', and 'Build normative model' were reported more frequently at graduate level. With respect to authentic design activities, *Explore user perspective* and *Encourage reflection on process* were the only two reported more frequently; whereas *Use functional decomposition, Explore graphic representation, Validate assumptions and constraints, Build normative model, Explore engineering facts, and Explore issues of measurement* were reported more frequently in artificial design activities.

It is evident in the literature that there is a dearth of research on the nature and extent to which engineering design skills outlined in the current U.S. *Framework for K-12 Science Education* and NGSS are addressed in widely used K-12 engineering education instructional materials. Yet, these engineering education curriculum materials continue to serve as main sources of engineering design activities for many science teachers, and science teacher educators. In view of the above, more attention to engineering design skills coverage in engineering design curriculum materials that are accessible to science teachers and science teacher educators is warranted as it may contribute to better teaching and learning of engineering design and science in schools, and science teacher education programmes. Our focus on engineering design skills in the widely used engineering education curriculum materials was also motivated by the implementation of NGSS in several schools in the U.S., and two National Association for Research in Science Teaching (NARST) 2014 position papers titled *Supporting the implementation of NGSS through research: Engineering*, and *Supporting the implementation of NGSS through research: Curriculum materials* (NARST, 2014a, 2014b). As such, investigating the coverage of engineering design skills in engineering education curriculum materials could yield data to inform the development of robust engineering design-integrated science units and activities. Furthermore, conducting this research could address one of the most cited challenges of implementing engineering design in science classroom – which is the lack of curriculum and instructional materials that integrate engineering design and science (Bamberger &

Cahill, 2013; Daugherty, 2012; Kimmel & Rockland, 2002). However, our analysis of the engineering education instructional materials for engineering design skills representation was not aimed at judging the *quality* of the engineering education curriculum materials or individual engineering education programmes or activities themselves. Instead, our goal was to report on the engineering design skills that were more salient to those who developed these curriculum materials and suggest improvements to serve students better.

Therefore, the purpose of this study was to determine the nature and extent of engineering design skills coverage in K-12 engineering education programmes curriculum materials that are widely used in U.S. schools. The study also sought to find out if there were differences in engineering design skills coverage in the curriculum materials across grade levels and disciplines. Three research questions guided this study: (1) What engineering design skills are emphasised in widely used K-12 engineering education curriculum materials? (2) What is the coverage of engineering design skills across grade levels (elementary, middle, and high school) in K-12 engineering education curriculum materials? (3) What is the coverage of engineering design skills across discipline-specific science subjects in K-12 engineering education curriculum materials?

The nature of engineering design skills coverage in the curriculum materials was determined by establishing the extent to which the following engineering design skills outlined in NGSS were represented: (a) *Defining and delimiting an engineering problem* (Defining and identifying an engineering problem; and Specification of clear goals, criteria, and constraints that the final product or system must meet); (b) *Developing possible solutions* (May begin with a relatively open-ended phase during which new ideas are generated via brainstorming; Communicating initial ideas through sketches, diagrams, concept maps, physical models, or computer simulations); (c) *Optimising the design solution* (Design/build/create/make; Test/show how a model/prototype works; Make iterations to improve the designs) (NGSS Lead States, 2013; NRC, 2012).

This study is significant for three main reasons: first, it goes beyond previous studies on engineering design in K-12 science classrooms by examining curriculum materials for engineering design skills representation. Second, engineering design has become explicitly recognised as an important outcome for K-12 students. Third, the curriculum materials we analysed are widely used in U.S. schools and other countries. As such, we anticipated that the findings in this study would be of significance to science teachers, science teacher educators, curriculum development experts, informal science instructors, and teacher professional development providers in the U.S. and other countries. For example, as science teacher educators understand the nature of engineering design representation in the activities or units they can design engineering-integrated science activities in their science methods courses or professional development programmes to enable science teachers to learn how to address engineering design skills that are not addressed in the curriculum materials we analysed.

Methodology

Data sources and selection criteria

Data sources were nine K-12 engineering education programmes whose focus has been developing engineering education curriculum materials in the U.S. (see Table 1). For a programme to be selected for inclusion in the analysis, it had to meet the following criteria: focus on science and engineering; be within the K-12 grade band; appears to have longevity; highlights number of schools served, teachers or students reached; and its learning materials, activities, or courses are accessible online. To locate the K-12 engineering programmes, several avenues were used. These included search engines and databases as well as queries in established publications in science education and engineering education journals. Several K-12 engineering education programmes were located, but those selected for review satisfied the selection criteria described above. Table 1 shows the K-12 nine engineering education programmes that were selected for analysis.

Table 1. K-12 engineering education programmes analysed.

Programme and developer	Maturity, impact/diffusion
Elementary school (grades K-5)	
Engineering is Elementary (EiE) (Boston Museum of Science)	Started in 2003. More than 20 units have been developed and field tested. Being used by about 15,000 elementary teachers and have impacted about one million students. *Website*: http://www.eie.org
City Technology (CT) (City College of New York)	Earlier curriculum guides were published in 2002 but did not have an engineering component. Currently Force and Motion and Energy Systems units are developed which integrate engineering. Earlier series were field tested in 19 U.S. states and more than 49 teachers have been trained to provide professional development in 16 states across the country. *Website*: http://www.citytechnology.org/stuff-that-works/home
Middle school (Grades 6–8)	
Engineering by Design™ (EbD) (International Technology Education Association (ITEA))	National Standards-Based Model Program built on the constructivist model that engages students in authentic, problem-based environment. EbD has a wider readership and implementers. *Website*: http://www.iteaconnect.org/EbD/ebd.htm
Gateway to Technology (GT) (Project Lead the Way)	Over 1400 schools in 50 U.S. states and District of Columbia are participating in PLTW programme. Analysis of 171 college transcripts showed 40% of students that completed PLTW pursued further education in technology and engineering fields in college. *Website:* http://www.pltw.org/our-programs/gateway
Learning by Design (LbD) (Georgia Institute of Technology)	Several articles and presentations have been developed. No exact numbers were given on students or teachers reached. *Website*: http://www.cc.gatech.edu/projects/lbd/home.html
A World in Motion (AWIM) (Society for Automotive Engineers)	Started in 1996. Used in all 50 U.S. states and in 10 of Canada's provinces. Over 60,000 kits have been shipped to schools since 1990. About four million students across North America have participated. More than 15,000 volunteer engineers have been involved in AWIM programs. *Website:* http://www.awim.org/
Engineering for Today's Intermediate School (ETIS) (Infinity)	Developed in 1999. Has trained over a thousand instructors. Currently being used in about 543 middle and high schools in 38 U.S. states and 9 countries. Has impacted thousands of students as they apply key concepts through hands-on engineering design projects. *Website:* http://www.smu.edu/Lyle/Institutes/CaruthInstitute/K-12Programs/InfinityProject
High school (grades 9–12)	
Principles of Engineering (PoE) (Project Lead The Way)	Over 1400 schools in 50 U.S. states and District of Columbia have participated. Analysis of 171 college transcripts showed 40% of students that completed PLTW classes pursued further education in technology and engineering fields as first-year college students. *Website:* http://www.pltw.org/our-programs/engineering/engineering-curriculum
Math for Innovators (MfI) (Infinity)	Developed in 1999. Has trained over a thousand instructors. Currently being used in about 543 middle/high schools in 38 U.S. states and 9 countries. *Website:* http://www.smu.edu/Lyle/Institutes/CaruthInstitute/K-12Programs/InfinityProject

Design and analysis framework

We employed the Multiple Comparative Case Study (Yin, 2009) research design. This design was appropriate because it allowed each K-12 engineering education programme to serve as an individual case with the opportunity to compare across the different programmes, or cases. The research team consisted of two STEM education experts and one engineering education expert. The former had K-12 teaching experience in life and physical sciences. The K-12 science education framework (NRC, 2012) was used as the analysis framework because it outlines the engineering design skills, with specific indicator ***phrases*** for each design skill (see highlighted text in Table 2). The anchoring ***phrases*** for each description of the design process skill served as an analysis and coding guide for researchers. For example, in GT programme unit 'Energy and the Environment', the task statement: *compare the temperature of different materials to determine which are better at preventing heat transfer,* was requiring students to determine the best materials, and was therefore coded under optimisation.

Units analysed

The units of analysis in this study were the lessons, units, or activities developed by the nine engineering education programmes. Since the number of units and science focus differ across programmes, we selected the analysis units based on the science focus, and the authors' science background knowledge in life, physical and earth sciences. The research team consisted of one life science, one physical and earth science, and one engineering education expert. This was done so that interpretations of the activities could be more accurate.

Since each K-12 engineering programme has its own personality in terms of the number of curriculum units developed and science content focus, the selection was based on three criteria: (a) if the K-12 programme covers all science disciplines (i.e. life science, physical science, and earth/space science), then one unit from each of the discipline was randomly selected. For example, Engineering is Elementary covers topics from three science disciplines, and one unit from each discipline was chosen. (b) If the K-12 programme only covered two science disciplines (e.g. life and physical sciences), we chose either two or one unit from either. (c) If the programme only covered one science discipline such as physical science for *A world in Motion programme*, we chose three different topics within the discipline. A total of 27 units were selected, 3 from each of the 9 programmes analysed, and are shown in Table 3.

Data analysis

The analysis of lesson units consisted of two initial phases of coding and rating of three randomly selected programme curricula for coders to get familiar with the process. Content analysis was conducted using line-by-line approach. The coding process was guided by the anchoring ***phrases*** for each engineering design skill as highlighted in Table 2. As such, the anchoring phrases for each description of the engineering design skill served as an analysis and coding guide for researchers. For example, in GT programme unit 'Energy and the Environment', the task statement: *compare the temperature*

Table 2. Engineering design skills in the new framework for K-12 science education.

Engineering design skills	Example phrases from some programme units
ETS1.A: Defining and delimiting engineering problems	
Defining and identifying an engineering problem	*CT unit on MechAninmations: Lesson 1 – Identifying and sorting mechanisms:* Each group is provided with a varied collection of manufactured mechanisms, such as can openers, scissors, nail clippers, etc. First, they make general observations about these devices. Then students look at common characteristics of these devices, and try to *determine what properties they share and problems with the mechanisms*. Finally, the groups sort their mechanisms according to their own secret categories, and challenge other groups to guess their categories
Specifying **goals, criteria, or constraints** that the final product or system must meet	*LbD unit on vehicles in motion goals:* Vehicles in motion challenges students to design and build a vehicle and its propulsion system *that can scale two hills and then continue as far and straight as possible.* *EbD Technological systems unit activities:* Students participate in engineering design *activities to understand how criteria, constraints, and processes affect designs*
ETS1.B: Developing possible solutions	
May begin with a relatively open-ended phase during which ***new ideas are generated via brainstorming***	*CT unit on MechAninmations*: Utilise both qualitative and quantitative analyses of existing designs (reverse engineering) to inform and/or evaluate designs and generate new ideas for designing improved designs. *LbD units:* Engages students in generating ideas during 'whiteboarding' and 'gallery walks'
Communicating initial ideas in various modalities such as sketches, diagrams, concept maps, physical models, or computer simulations	*CT units:* Communication of ideas is mainly via use of physical models to illuminate the subtle technologies that are embedded in everyday devices such as toys, tools, and simple machines. *GT units:* The construction and testing of a model is the primary vehicle used to facilitate hands-on experiences. For example, in the *Flight and Space* unit, students design and test air foils, and the performance during testing provides tangible feedback regarding the effectiveness of their ideas as well as the quality of their design
ETS1.C: Optimising the design solution	
Determining what constitutes 'best,' by making trade-offs among competing criteria	*EiE unit on water, water everywhere: designing water filters:* Students weighed in on trade-offs by determining which filtering materials would cost less or more. *AWIM units on motorised toy car and glider:* Both ask students to balance the trade-offs between competing variables. For example, the sequence of inquiry investigations and analysis in the motorised toy car unit leads to designing a vehicle that strikes a balance between a gear ratio and proportion of wheel radius
Designing prototypes	
Design, build, and make a model/prototype	*EiE unit on just passing through: designing water filters*: Lesson 4 requires students to design a model membrane that will dispense water in a controlled manner for an imaginary frog *EbD unit on technological systems: how they work: lesson 2 extension activity* requires students to design and build a passive sound barrier that will reduce the noise from an air pump or other noisy device. *GT unit on flight and space:* Lesson 4.2 requires students to design an air foil that will create lift using a wing tester
Testing prototypes	
Test, show, or demonstrate how a model or prototype works	*EbD unit on technological systems: how they work: Lesson 1 extension activity* requires students to design and use/test a simple communication system to send and receive a message

(*Continued*)

Table 2. Continued.

Engineering design skills	Example phrases from some programme units
Making iterations	
Make **iterations to improve** designs	*LbD unit on vehicles in motion's rubber-band car mini-challenge*: Students designed the car and iteratively tested it and redesigned it so it could go faster than their first test *CT unit on MechAnimations*: Lesson 8 requires students to design their own MechAnimations, and have an opportunity to revise their designs

The text in ***bold*** represents the anchoring **phrases** that served as analyses and coding guides for researchers.

Table 3. Science lesson units selected for analysis.

Grade level	K-12 programme	Units selected for analysis and science foci
Elementary school (grades K-5)	Engineering is Elementary	• Just passing through: designing model membranes (LS) • To get to the other side: designing bridges (PS) • Water, water everywhere: designing water filters (ESS)
	City Technology	• MechAnimations (Force and Motion – PS) • Invent-a-Wheel (Energy Systems – PS) • ElectroCity units (Energy systems – PS)
Middle school (Grades 6–8)	Engineering by Design	• Technological systems: how they work (PS) • Technological systems: issues and impacts (PS) • Technological systems interactions (PS)
	Gateway to Technology	• Energy and the environment (PS) • Flight and space (ESS) • Medical detectives (LS)
	Learning by Design	• Apollo 13 (engineering design process) • Vehicles in Motion (PS) • Tunnelling across Georgia (ESS)
	A World in Motion	• Gravity cruiser (PS) • Motorised Toy Car (PS) • Glider (PS)
	Engineering for the Intermediate School	• Sound engineering: making great sounds (PS) • Engineering in the Natural World (ESS) • Engineering the Human Machine (LS)
High school (Grades 9–12)	Principles of Engineering	• Energy and power (PS) • Materials and structures (PS) • Control systems (PS)
	Math for Innovators	• Engineering our Environment (ESS) • The Human Body as a Biomachine (LS) • Sounds of a Digital Age (PS)

Note: PS: physics science; ESS: earth and space science; LS: life science.

of different materials to determine which are better at preventing heat transfer, required students to determine the best materials, and was therefore coded under optimisation.

The inter-rater reliability was established between the two coders. Due to the presence of the anchoring phrases, the coding process was quite consistent. The coefficient of inter-coder agreement was calculated (Cohen, 1960). The two coders coded all units selected, and were in agreement on average of 80.35% of the time. After coding, the learning units for each K-12 engineering education programme were classified for the nature and extent to which engineering design process skills were covered. If the engineering design skill was addressed by seven to nine programmes (78–100%), it was described as ***high coverage***; if it was addressed by four to six programmes (44–67%) it was described as ***medium coverage***; and if it was addressed by one to three programmes (11–33%), the engineering design skill was described as ***low coverage***; and if no programme addressed it, it was described ***no coverage***.

Results

Coverage of engineering design skills

Table 4 shows the engineering design skills which were covered in the K-12 engineering education curriculum materials analysed.

As shown in Table 4, *developing possible solutions* (via brainstorming, and communicating ideas through sketches, diagrams, models, simulations), and *actual designing of models/prototypes* were the highly covered design skills; *specification of clear goals, criteria, and constraints that the final product or system must meet* had a medium coverage; *defining and identifying an engineering problem, optimising design solution, testing or demonstrating how a model/prototype work, and making iterations to improve the designs* were lowly covered. Salient observations we noted during the analysis were (a) generally *defining and identifying engineering problems* is either explicit or implicit or non-existent in most engineering education programmes; (b) individual programmes defined engineering problems using different strategies which included questioning, analysis of existing designs (reverse engineering design); (c) most of the curricula did not explicitly address the concept of optimisation, but it was often embedded in lessons rather than stipulated explicitly in learning activities; and (d) virtually all programme curricula utilised different engineering design processes, but all with a common goal of presenting a paradigm for designing solutions to human problems that included a cyclical pattern of steps.

Table 4. Coverage of engineering design skills in K-12 engineering education programmes.

Engineering design skills	Extent of coverage	# K-12 programmes	Engineering programme abbreviations
ETS1.A: Defining and delimiting an engineering problem			
Defining and identifying an engineering problem	Low	2 (22%)	EiE and CT
Specification of clear goals, criteria, and constraints that the final product or system must meet	Medium	4 (44%)	EiE, CT, LbD, and EbD
ETS1.B: Developing possible solutions			
May begin with a relatively open-ended phase during which new ideas are generated via brainstorming	High	7 (78%)	EiE, CT, LbD, GT, AWIM, PoE, and MfI
Communicating initial ideas through sketches, diagrams, concept maps, physical models, or computer simulations	High	7 (78%)	EiE, CT, LbD, GT, EbD, AWIM, and PoE
ETS1.C: Optimising the design solution			
Determining what constitutes 'best,' by making trade-offs among competing criteria	Low	3 (33%)	EiE, LbD, and AWIM
Designing			
Design, build and make a model/prototype	High	9 (100%)	EiE, CT, LbD, GT, EbD, ETIS, AWIM, PoE, and MfI
Testing prototypes			
Test/show/demonstrate how a model/prototype works	Low	2 (22%)	EiE and LbD
Making iterations			
Make iterations/refinements to improve the designs	Low	1 (11%)	EiE

Note: EiE: Engineering is Elementary; CT: City Technology; LbD: Learning by Design; GT: Gateway to Technology; EbD: Engineering by Design; ETIS: Engineering for Today's Intermediate School; AWIM: A World in Motion; PoE: Principles of Engineering; MfI: Math for Innovators.

High coverage

Developing possible solutions and *actual designing of models/prototypes* are highly covered in most K-12 engineering education curricula that were analysed. With respect to developing possible solutions via brainstorming, nearly all programmes had learning activities that involved students in generating possible solutions to a problem or challenge, though the strategies varied from one engineering education programme to the other. For example, CT engineering education curricula utilised both qualitative and quantitative analyses of existing designs (reverse engineering) to inform and/or evaluate designs and generate new ideas for designing improved designs. To the contrary, LbD curricula engaged students in generating ideas during 'whiteboarding' and 'gallery walks'. With respect to communicating initial ideas through sketches, diagrams, models, or simulations, our analyses revealed that most activities (78%) engaged students in communicating ideas via modelling usually from everyday materials, or sketches. For example, EiE projects engaged students in building models such as membranes, water filters, paper bridges, and alarm systems. Specifically, the unit *Just Passing Through: Designing Model Membranes* involved students in designing a model membrane through which water can pass at a given rate. For CT, communication of ideas is mainly via physical models to illuminate the subtle technologies that are embedded in everyday devices such as toys, tools, and simple machines. During the course of learning units, these models serve as hands-on manipulatives, and tangible representations of student thinking. In GT, the construction and testing of a model was the primary vehicle used to facilitate hands-on experiences. For example, in the *Flight and Space* unit, students design and test airfoils, and the performance during testing provides tangible feedback regarding the effectiveness of their ideas as well as the quality of their design. Additionally, models are also used to illustrate phenomena. For instance, in the unit Energy and the Environment, students analyse different model materials to determine which ones are better at preventing heat transfer. To the contrary, other programme materials (e.g. AWIM units), models, and modelling are not among the core concepts being addressed in the unit goals, although they play integral roles in lesson activities. They enable students to visualise their design ideas in a tactile and concrete manner. Furthermore, from an engineering point of view, the models that students build and test provide the data needed to make informed design decisions. This application of models is consistent with how modelling is used in many engineering contexts. All programmes involved students in designing some kind of artefacts.

Medium coverage

The engineering design skill – *Specification of clear goals, criteria, and constraints that the final product or system must meet* – had a medium coverage by 44% of the programmes. Generally, our analyses revealed that most programme curricula that addressed constraints presented them as *things* particularly time, money, and materials that limit the design process (in EiE and LbD programmes); whereas CT included rules among constraints on the design process, and GT includes aesthetic considerations.

In EiE, specification of constraints is placed in the 'Ask' phase where students identify the constraints, although the treatment of constraints such as time, money, or materials was irregular and less decisive. That is, rich discussions of the constraints associated with a given problem were not explored in any depth, but tend to be more implied than defined explicitly.

In CT, curriculum utilises a *reverse engineering design* strategy for students to analyse existing designs of everyday devices to determine how they work, common characteristics, while giving lots of attention to establishing and meeting design criteria. In this context, design criteria are the things that the design must meet in order to be considered successful or acceptable. Students are asked to identify design criteria, address the criteria as they design the artefacts, and evaluate the final design in relation to the design criteria.

Other programmes such as GT and PoE's learning activities do not require students to specify constraints. Instead, the parameters for a successful solution to a problem in the form of sets of rules are stated or implied in the materials provided for investigations.

In some programmes such as A World in Motion, the concept of constraints is not one of the main ideas required of students to conceptualise in the units of instruction. However, the uncompleted prototypes sent by fictitious companies provide students with an investigation basis for uncovering many of the natural variables that govern vehicle performance (e.g. friction, forces, weight). Furthermore, though the correspondences from the fictitious companies outline the expectations for the final designs, they are more consistent with the concept of design specifications than constraints.

Low coverage

This was evident in three engineering design skills which are: *Defining and identifying an engineering problem; Optimising (i.e. determining what constitutes 'best,' by making trade-offs among competing criteria); Testing or demonstrating how a model/prototype works*, and *Making iterations to improve the designs.*

Our analyses generally revealed that *defining and delimiting engineering problems* is either explicit or implicit or non-existent in most programmes. Furthermore, we found that individual programmes define the engineering problems using different strategies that include questioning, analysis of existing designs (reverse engineering design). For example, in EiE, problem definition is placed in the 'Ask' phase where students identify the problem from the storybook. During the 'Ask' phase students address questions like: 'What is the problem?' 'What have others done?' An example is found in the video on the unit *Water, Water Everywhere*, where students were involved in filling out a worksheet on the types of pollution, sources, and solutions. CT is one of the few curricula that engage students in identifying and defining a problem. The units utilise a *reverse engineering design strategy* for students to define the problem. Specifically, most of the learning activities involve collecting, organising, and analysing data from existing designs, which is then used to define the problem, make a design decision, redesign the artefacts, and conduct evaluations. In A World in Motion units, students are not directly engaged in initial problem identification. Instead, the materials challenge students to analyse the contents of a letter or request for proposals from fictitious companies to identify the problem and specifications of a successful solution. In GT and PoE curricula, most learning activities do not ask students to define the problem. Instead, the materials state the parameters for a successful solution to a problem in the knowledge and skills sections for each unit, and the constraints are presented to the students as sets of rules or implied in the materials.

With respect to *optimising the design solutions*, very few programmes (33%) explicitly address the concept of optimisation. For example, in EiE, students weighed in on trade-offs by determining which filtering materials would cost less or more in the unit *Water,*

Water Everywhere: Designing Water Filters. In AWIM units on *Motorised Toy Car* and *Glider* units, optimisation is part of the essence of these activities. Both units ask students to balance the trade-offs between competing variables. For example, the sequence of inquiry investigations and analysis in the Motorised Toy Car unit leads to designing a vehicle that strikes a balance between a gear ratio and proportion of wheel radius. These units emphasise the application of science and math principles in the context of doing inquiry. One point to note is that none of these curricula included procedures for conducting a formal analysis of competing criteria such as a trade-off matrix for making quantitative comparisons of the strengths and weaknesses of competing designs. Majority of the programmes do not explicitly involve students in optimising design solutions. Instead, this concept is often embedded in lessons rather than stipulated explicitly in unit goals, learning activities, or assessments. Another note is that optimisation is most often embedded in the concepts of iteration and redesign, with a goal to improve a design. However, improving a design is not always synonymous with making trade-offs. For example, CT units do not involve students in determining the best design, but they do expose them to concepts of trade-offs and redesign. Similarly, GT units state the parameters for a successful solution to a problem in the knowledge and skills sections for each unit, but students are not directly engaged in addressing the balance between competing factors. For example, in GT unit on *Flight and Space,* the lesson understandings include effects of gravity, thrust, lift, and drag on an aircraft's performance, but the main goal in one of the lesson activities was simply for students to design and test an airfoil's performance without probing students to deliberately confront the trade-offs of airfoil's gravity, thrust, or lift.

Although all programmes had high coverage of actual designing of artefacts, very few (22%) did actually require students to further *test or demonstrate how those artefacts (models or prototypes)* work.

Similarly, *making iterations to improve the designs* was rarely incorporated in the analysed units. The few that engaged students in this skill include LbD unit on *Vehicles in Motion*'s Rubber-band car Mini-Challenge where students designed the car and iteratively tested it and redesigned it so it could go faster than their first test.

Coverage of engineering design skills across grade levels

As shown in Table 5, more engineering education programmes addressed individual design skills differently. Salient observations showed that most of the design skills were addressed by at least half or all of the programmes at elementary and high school levels. One argument for this finding could be that the elementary and high school engineering programmes (i.e. EiE, PLTW's PoE, and Infinity's MfI) are the most widely used and have recently updated their learning units to fit with the calls for engineering integration in science. Specifically, the two elementary programmes addressed most of the engineering design skills except for *optimisation of design solution*, and *making iterations*. Similarly, many design skills were addressed by more than half of the middle school level programmes except *defining and identifying an engineering problem; specifying criteria and constraints; optimisation; testing prototypes;* and *making iterations*. Similar trends were observed in high school programmes in which *Defining and identifying an engineering*

Table 5. Coverage of engineering design skills across grade levels.

Engineering design skills	Elem (*n* = 2)	Middle (*n* = 5)	High school (*n* = 2)
ETS1.A: Defining and Delimiting an Engineering Problem			
Defining and identifying an engineering problem	2 (100%)	–	–
Specification of clear goals, criteria, and constraints that the final product or system must meet	2 (100%)	2 (40%)	–
ETS1.B: Developing possible solutions			
May begin with a relatively open-ended phase during which new ideas are generated via brainstorming	2 (100%)	3 (60%)	2 (100%)
Communicating initial ideas through sketches, diagrams, concept maps, physical models, or computer simulations	2 (100%)	4 (80%)	1 (50%)
ETS1.C: Optimising the design solution			
Determining what constitutes 'best,' by making trade-offs among competing criteria	–	2 (40%)	1 (50%)
Designing artefacts			
Design, build or make a model/prototype	2 (100%)	5 (100%)	2 (100%)
Testing prototype			
Test or show how a model/prototype works	–	2 (40%)	–
Making iterations			
Make iterations/refinements to improve the designs	–	1 (20%)	–

problem; specifying criteria and constraints; optimisation; testing prototypes; and *making iterations* were either lowly covered or not covered at all.

Coverage of engineering design skills across science discipline-specific units

Table 6 revealed the following observations: (a) most of design process skills were addressed in physical science units, followed by earth/space science units; and least in life science units; (b) actual designing of artefacts was the highly covered design skill in all discipline units; (c) *Specification of criteria and constraints; brainstorming; communicating initial ideas;* and *optimisation* had medium coverage in physical science units, but had low or no coverage in life and earth science units; (d) *Testing/showing how a model/prototype works,* and *Making iterations to improve the designs* were lowly covered in life and physical science units and not addressed in earth science units.

Discussion and conclusion

The results show that *brainstorming of new ideas and alternatives; communicating initial ideas through sketches, diagrams, concept maps, physical models or computer simulations;* and *actual designing* are the highly covered engineering design skills in the K-12 engineering education programmes that were analysed. The high coverage of the design skill *generating new ideas or exploring new alternatives* was consistent with the findings reported by Mehalik and Schunn (2006) and Gómez Puente et al. (2011). However, *Communicating initial ideas through sketches, diagrams, concept maps, physical models or computer simulations*, and *actual designing skill* were reported moderately in Mehalik and Schunn (2006), and were not investigated in Gómez Puente et al. (2011). The design skill of *specification of clear goals, criteria, and constraints* received a medium coverage in engineering education curricula materials. This finding was similar to that of Mehalik and Schunn (2006), but different from Gómez Puente et al. (2011) who reported a high coverage of this design skill. In our study, the lowly covered engineering design skills included: *defining and*

Table 6. Coverage of engineering design skills across discipline-specific units.

Engineering design process skills	Life science units ($n = 4$)		Physical science units ($n = 18$)		Earth science units ($n = 5$)	
ETS1.A: Defining and delimiting an engineering problem						
Defining and identifying an engineering problem	25%	EiE^{1}	33%	EbD^{1,2,3} and PoE^{1,2,3}	–	–
Specification of clear goals, criteria, and constraints that the final product or system must meet	25%	EiE^{1}	50%	EiE^{2}, LbD^{1,2}, EbD^{1,2,3} and PoE^{1,2,3}	40%	EiE^{3} and LbD^{,3}
ETS1.B: Developing possible solutions						
May begin with a relatively open-ended phase during which new ideas are generated via brainstorming	25%	EiE^{1}	50%	EiE^{2},LbD^{1,2,3}, AWIM^{1,2} and PoE^{1,2,3}	20%	EiE^{3}
Communicating initial ideas through sketches, diagrams, concept maps, physical models, or computer simulations.	25%	EiE^{1}	44%	CT^{3}, LbD^{1,2}, AWIM^{2,3} and PoE^{1,2,3}	20%	LbD^{,3}
ETS1.C: Optimising the design solution						
Determining what constitutes 'best,' by making trade-offs among competing criteria	25%	EiE^{1}	44%	CT^{1},LbD^{1,2,3}, GT^{1} and PoE^{1,2,3}	–	–
Design/build/create/make	75%	EiE^{1}, ETIS^{3} and MfI^{2}	83%	EiE^{2}, CT^{1,2,3}, LbD^{1,2,3}, GT^{1}, EbD^{1,3}, ETIS^{1}, PoE^{1,2,3} and MfI^{3}	48%	EiE^{3}, GT^{2}, EbD^{1,3}, ETIS^{2} and MfI^{1}
Test/show how a model/prototype works	25%	EiE^{1}	11%	LbD^{1} and EbD^{1}	20%	LbD^{3}
Make iterations to improve the designs	25%	EiE^{1}	11%	CT^{1,2}	–	–

Note: Superscripts represent the number of lesson unit, for example, GT^{1} represents Gateway To Technology unit 1: Life science units: *EiE* unit 1 – Just passing through: designing model membranes; *GT* unit 3 – Medical detectives (LS); *ETIS* unit 3 – Engineering the Human Machine (LS); *MfI unit 2* – The Human Body as a Biomachine. Physical science units: *EiE* unit 2 – To get to the other side: designing bridges. *CT* unit 1 – MechAnimations, unit 2 – Invent-a-wheel, and unit 3 – ElectroCity. *LbD* unit 1 – Apollo 13 (design process) and unit 2 – Vehicles in Motion (PS). *GT* unit 1 – Energy and the environment; EbD module unit 1 – Technological systems: how they work, unit 2 – Technological systems: issues and impacts, and unit 3 – Technological systems interactions; ETIS module unit 1 – Sound engineering; making great sounds; AWIM unit 1 – Gravity cruiser, unit 2 – Motorised Toy Car, and unit 3 – Glider; PoE unit 1 – Energy and power, unit 2 – Materials and Structures, and unit 3 – Control systems; MfI unit 3 – Sounds of a digital age. Earth/space science units: EiE unit 3 – Water, water everywhere: designing water filters; LbD unit 3 – tunnelling across Georgia (ESS); GT unit 2 – Flight and space; ETIS module unit 2 – Engineering in the Natural World; MfI unit 1 – Engineering our Environment (ESS).

identifying engineering problem, optimising design solution, testing/demonstrating how a model/prototype works, and *making/using iterations to improve the designs*. These findings were either supported or not supported by previous studies. For example, Mehalik and Schunn (2006) and Gómez Puente et al. (2011) reported high coverage of *defining and identifying engineering problem*, and making *iterations to improve the designs*, but our results show low coverage of both skills. Our finding on the low coverage of the design skill *optimising design solution* was supported by Gómez Puente et al. (2011), but not by Mehalik and Schunn (2006) who found a moderate coverage.

The varying degrees of coverage for engineering design process skills revealed in this study are a point of concern as the U.S. schools move towards full integration of engineering design skills in K-12 science classrooms through NGSS. Additionally, there is a concern in the imbalance in which engineering design skills were mostly evident in physical science units than in life and earth science units. The fact that *actual designing of artefacts* was highly covered, but with less emphasis on *testing or demonstrating how a model/prototype works,* and *making iterations to improve the design* may erroneously suggest that engineering is only associated with building and construction activities, and not with other design skills. This observation is supported by Windschitl, Thompson, and Braaten (2008) who argued that a few science teachers who employ models tend to use them as end products of inquiry rather than as tools to help students explain and generate knowledge about concepts being illustrated at any point in the inquiry. Similarly, the NARST (2014b) position statement also warns that while building prototypes is critical during design, these prototypes should not be the end goal but rather be used to start infusing other design skills such as discussion, argumentation, design evaluation, and further data collection. Therefore, as science and engineering educators and researchers continue to push for integration of engineering design process skills in K-12 science classrooms, it is vital to integrate the design skills in a manner that would help students use the design skills as knowledge generation and knowledge application contexts and tools. This implies that curriculum units should engage students in all design skills, should therefore be addressed adequately in science curriculum materials. However, this was not the case with the K-12 engineering education programme materials we analysed. As such, understanding which and to what extent engineering design skills are covered in K-12 learning units is imperative. The engineering design skills stipulated in the *K-12 science education framework and NGSS* can be used as a tool for evaluating the degree to which learning units address engineering design, and it can be used to inform the development and structure of future K-12 learning units.

For the integration of engineering design to serve as an anchoring context for science learning, curriculum materials should not only emphasise the actual design of artefacts, but also other skills such as *defining and identifying engineering problem, optimising design solution, and testing or demonstrating how a model/prototype works* and *making iterations to improve the* designs. If students can articulate the problem, specify the constraints along the way, and determine the best solution for the design problem, then teachers would be assured that students are making the needed connections. Therefore, these findings should communicate to science teachers about the importance of engaging students in familiar and real-world engineering problems which they can articulate well, and consequently articulate constraints, and engage in reasonable optimisation process. If students are not very clear about the science questions and an articulate engineering problem from the onset, they may not learn as intended by the new K-12 science education framework.

The current study was on the analyses of instructional materials in nine widely used K-12 engineering education programmes. To get a holistic understanding of how engineering design skills are addressed in science classrooms, we propose that future studies should involve lesson observations to document how engineering design skills in these nine programmes curricula are addressed in science classrooms. In addition, we propose that it would be vital to investigate which engineering design skills are considered relevant by science teachers depending on whether they are introducing the unit, are in the middle, or at the end of the unit. Such data would be helpful in assessing how design activities should be structured based on when specific design skills would be appropriately emphasised. Of critical importance too, is another study on how student learning would be enhanced when taught in the context of engineering design skills stipulated in the New Framework for K-12 Science Education. Such a study would provide insights into what kinds of instructional models would enhance science learning. So far an explicit instructional model for teaching science and engineering design is missing (Bamberger & Cahill, 2013; Daugherty, 2012).

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References

Apedoe, X., Reynolds, B., Ellefson, M., & Schunn, C. (2008). Bringing engineering design into high school science classrooms: The heating/cooling unit. *Journal of Science Education and Technology*, *17*(5), 454–465.

Bamberger, Y. M., & Cahill, C. S. (2013). Teaching design in middle-school: Instructors' concerns and scaffolding strategies. *Journal of Science Education and Technology*, *22*(2), 171–185.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*, 37–46.

Crismond, D. (2001). Learning and using science ideas when doing investigate-and-redesign tasks: A study of naive, novice, and expert designers doing constrained and scaffolded design work. *Journal of Research in Science Teaching*, *38*(7), 791–820.

Cunningham, C. M., Lachapelle, C., & Lindgren-Steicher, A. (2005). *Assessing elementary school students' conceptions of engineering and technology*. Proceedings of the 112th ASEE Annual Conference and Exposition, Portland, OR.

Daugherty, J. (2012). *Infusing engineering concepts: Teaching engineering design*. National Center for Engineering and Technology Education. Retrieved from www.ncete.org.

Gómez Puente, S. M., van Eijck, M., & Jochems, W. (2011). Towards characterising design-based learning in engineering education: A review of the literature. *European Journal of Engineering Education*, *36*(2), 137–149.

Kimmel, H., & Rockland, R. (2002, November). *Incorporation of pre-engineering lessons into secondary science classrooms*. Proceedings of the 32nd ASEE/IEEE frontiers in education conference, Boston, MA.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., … Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by Design^{TM} into practice. *Journal of the Learning Sciences*, *12*(4), 495–547.

Mehalik, M. M., Doppelt, Y., & Schunn, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education*, *97*(1), 71–85.

Mehalik, M. M., & Schunn, C. (2006). What constitutes good design? A review of empirical studies of design processes. *International Journal of Engineering Education*, *22*(3), 519–532.

National Academy of Engineering. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research* (M. Honey, G. Pearson, & H. Schweingruber, Eds.). Washington, DC: The National Academies Press.

National Association for Research in Science Teaching. (2014a, August 10). *Position paper: Supporting the implementation of NGSS through research: Curriculum materials* (J. Carlson, E. A. Davis, & C. Buxton, Eds.). Retrieved from https://narst.org/ngsspapers

National Association for Research in Science Teaching. (2014b, August 10). *Position paper: Supporting the implementation of NGSS through research: Engineering* (S. Purzer, T. J. Moore, D. Baker, & L. Berland, Eds.). Author. Retrieved from https://narst.org/ngsspapers

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington, DC: The National Academies Press.

Penner, D. E., Giles, N. D., Lehrer, R., & Schauble, L. (1997). Building functional models: Designing an elbow. *Journal of Research in Science Teaching*, *34*(2), 125–143.

Penner, D. E., Lehrer, R., & Schauble, L. (1998). From physical models to biomechanics: A design-based modeling approach. *Journal of the Learning Sciences*, *7*(3/4), 429–449.

Resnick, M., Berg, R., & Eisenberg, M. (2000). Beyond black boxes: Bringing transparency and aesthetics back to scientific investigation. *Journal of the Learning Sciences*, *9*(1), 7–30.

Rogers, C. B., Wendell, K., & Foster, J. (2010). A review of the NAE report, engineering in K-12 education. *Journal of Engineering Education*, *99*(2), 179–181.

Roth, W.-M. (1996). Art and artifact of children's designing: A situated cognition perspective. *Journal of the Learning Sciences*, *5*(2), 129–166.

Sadler, P. M., Coyle, H. P., & Schwartz, M. (2000). Engineering competitions in the middle school classroom: Key elements in developing effective design challenges. *Journal of the Learning Sciences*, *9*(3), 299–327.

Wendell, K. B., & Lee, H. S. (2010). Elementary students' learning of materials science practices through instruction based on engineering design tasks. *Journal of Science Education and Technology*, *19*(6), 580–601.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*, 941–967.

Yin, R. K. (2009). *Case study research: Design and methods* (4th ed.). Thousand Oaks, CA: Sage.