Technology design and engineering design: Is there a difference?

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Abstract

Design is a core concept across many domains with varying perspectives on its definition that are often field-specific. Particularly within the closely related domains of technology and engineering, the definition and practical applications of design are not clearly differentiated. More recently the conversation has turned to design within STEM education further complicating the discussion. This conceptual overlap requires clarity so that design can be better situated within educational contexts across the K-16 spectrum. Many have offered disciplinary perspectives on design within engineering and technology. This paper explores these perspectives in an attempt to address the question: what similarities and differences exist between technology design and engineering design? This is an important question because in order to best teach design within technology education it is important to identify its representative vocabulary by clarifying the terminology for coherence and consistency. The purpose of this paper is to provide a framework for design within K-16 technology education. In so doing, the authors conducted a review of technology and engineering design definitions and educational models. The paper ends with the authors envisioning a model for K-16 technology education that represents a synergy between the strengths of both technology and engineering titled “sTEm design.” The concept of sTEm design is based on the application of mathematic and scientific principles governing our physical world to inform design decisions and presents an opportunity to bring ideas into tangible reality.

Introduction

Design is a core concept and activity across many domains within the arts and sciences. Fields including interior design and architecture anchor their practice on design. Thus there are varying perspectives on the definition of design that are often field-specific. Within the closely related domains of technology and engineering, the definition and practical applications of design are not clearly differentiated. This conceptual overlap requires clarity so that design is better situated within technology education across the K-16 spectrum, which has implications for the teaching and learning environment. The ultimate issue is the identification of the learning outcomes associated with design. The difficulty of defining “the residue of knowledge that should result from the design teaching process itself” has been noted as one of the problems with design education [1]. Without clarity as to what design means within technology education and an appropriate educational framework, the targeted learning outcomes are less clear and distinct.

As technology and engineering are disciplines within their own right with design serving to anchor both domains, it is important to determine how their conceptualizations of design overlap and are distinguished in the literature. Many have attempted to offer disciplinary perspectives on design; more so within engineering but as well within technology. However, few, if any, have articulated an educational framework for the teaching and learning of technology design across the K-16 spectrum. This paper explores perspectives on design in an attempt to address the question: what similarities and differences exist between technology design and engineering design? The intent with this exploration is to better understand design within technology education and to articulate an educational framework for the teaching and learning of design. In this pursuit the discipline of technology and engineering is explored, as well as the literature on design within each discipline. The educational implications are discussed and in so doing an educational framework for K-16 technology education is offered under the banner of “sTEm design.”

Discipline of Technology

To better understand technology design, it is important to briefly define the discipline of technology. The roots of technology as a discipline can be traced to Tekhne; the early Greek word meaning “art” or “craft.” Tekhne [techne] “combines the meanings of an art and a technique, involving both a knowledge of the relevant principles and an ability to achieve the appropriate results” [2]. The Greeks made the distinction between nature and the products of human activities. Nature maintains its existence through reproduction, while other things require intervention by humans to exist (design). The etymology of the words “technique” and “technology” demonstrate a preservation of the meaning of Tekhne in the current discipline of technology [3].

The discipline of technology can be divided into two foci: (a) the study of technology and (b) the application of technology, both containing elements of technological knowledge [4].The knowledge component associated with the study of technology has been differentiated from scientific knowledge [5]. The pursuit and ideals of science seek to understand the governing principles of the world around us. Technological knowledge is demonstrated in the development of a technological artifact; sometimes even prior to the scientific understanding governing its function or production processes. Much more than simply the application of scientific knowledge, technological knowledge displayed in the application of technology is intimately associated with the needs and values of users; a dimension of the social system. Further expounding on the knowledge dimension of technology, Vinceti pointed out three categories of technological knowledge: (a) descriptive, (b) prescriptive and (c) tacit.

Descriptive knowledge includes the factual information, such as material properties, that provides the framework within which the individual works. Prescriptive knowledge emerges from "successive efforts to achieve greater effectiveness, such as improved procedures or operation, and is altered and added to as greater experience is gained" [6]. Tacit knowledge results from practice and experience and is less identifiable then prescriptive and descriptive knowledge. These three categories of technological knowledge can form important dimensions of an educational approach to technology as an educational discipline, with design learning across all three categories.

Indicating the growing importance of the technology discipline, the U.S. National Academy of Engineering and the National Research Council assembled a Committee on Assessing Technological Literacy in 2006 to establish a common understanding of technology, its importance, and recommendations of how best to achieve technological literacy because "an understanding of what technology is, how it works, how it is created, how it shapes society, and how society influences technological development is critical to informed citizenship" [7]. The committee's definition of technology focused on the process of modifying nature to meet needs and wants, which includes tangible products and the knowledge and processes used to create them. This definition of technology provides a rationale for the technological design process as an integral aspect of technology education.

Discipline of Engineering

Although it may appear that engineering schools have emphasized the theory of engineering design over the practical application of design; history reveals that early engineering programs emphasized both the theory and practical application of engineering. The first engineering program in the United States began at West Point in the early 1800's [8]. The first example of a private American civil engineering school in the United States began in 1835 under the direction of Van Rensselaer, who was the founder of Rensselaer Polytechnic Institute in Troy, New York. The school was based on the teaching of the sciences with practical application, such as employing the knowledge of mechanics to the technology of steamboats, mills, and factories. The practical applications of engineering education at Rensselaer also included surveying; computing water pressures in locks, aqueducts, dams; as well as designing and planting outdoor gardens for research purposes [9].

These early engineering schools blended the theory and practice of engineering design. However, perhaps the most well known example of this approach to teaching engineering was Worchester Technical Institute, founded by Boynton and Washburn in 1865. Washburn's contribution to the university curriculum was unique; a machine shop to provide a practical application of the engineering science instruction. A new type of mechanical engineering course emerged; "a course which combined experience in a shop…..and a theoretical course in applied science and engineering" [10]. Bennett wrote that the purpose of the shop was not for manual or industrial training but for an educational purpose; the machine shop was to engineering as a laboratory is to science. The work done in the machine shop was to be a substitute for an apprenticeship, while simultaneously taking courses in mathematics, science, and engineering. The news spread about the success of this educational approach and other universities around the country began to introduce shop work into their engineering programs [11].

Over time there was a shift in thinking about the best pedagogical approach to teaching engineering. Wankat et al. suggested that the many engineering professors who emigrated from Europe after World War I spurred on this new way of teaching engineering that focused more science and mathematics. They also indicated that this shift in engineering pedagogy did not happen suddenly, but rather over time. The pace accelerated during World War II to meet the demand for engineers with empirical research capabilities necessary to keep up with the need for innovations in human made materials and processes. This demand for emphasis in academic research in engineering schools culminated in the early 1950s with the space race at which point the American Society for Engineering Education committee prepared the Grinter Report. This report called for a greater emphasis in the mathematical and scientific elements of engineering. The focus shifted away from the practical application of engineering to a theoretical and "engineering science" approach to the teaching of engineering and an emphasis on "scientific analysis and mathematical modeling" [12].

This history of engineering education has had a profound impact on how engineering schools approach teaching design within their engineering programs. Dym organized the views on the teaching of design in engineering programs into three general schools of thought [13]. The first view of design in engineering supports the notion that design is experimental in nature and that the creative element within the design process cannot be taught. This view of design advises against using a scientific approach to design, which limits creativity and would likely result in generating an abstract and sterile outcome. The second view of engineering design, however, is generated from the views of engineering scientists, with the opinion that there is no real context to teaching design. This contingent approach indicates that there is no meaningful design curriculum unless it can be expressed mathematically. The third view is that design, through a focus on scientific inquiry, allows for a broader view of the design process to embrace design as a cognitive activity. Dym proposed an integration of all three views for teaching engineering design. He suggested embracing the experimental nature of design, while also considering that design is a cognitive, creative activity.

Approaches to Design

Reflecting upon the brief history and philosophical orientation of technology and engineering, a rationale emerges explaining how these two disciplines have taken diverging approaches to teaching design. Within technology education, the emphasis has been on the applications and artifacts of technological knowledge and the societal impacts of the designed world. The emphasis within engineering has been on the experimental nature of design and its scientific and mathematical underpinnings. The following sections highlight various technology design models and engineering design models as a way to further compare their similarities and differences, particularly in their educational approaches.

Technological Design

Technology design as a concept or activity has not been well explored in the literature as compared to the discipline of technology. In addition, at the K-12 level, many have called for the integration of engineering design into technology education [14, 15, 16, 17], blurring any distinctions between the two. However, some researchers and educators have explicitly articulated and discussed a technology design process. Layton, for example, argued that design was the central purpose of technology, which has multiple dimensions including an adaption of means to some preconceived end [18].

Most of the writing on technological design is rooted in the literature focused on technology education. Table 1 outlines the design steps associated with three such technological design models. The Committee on Assessing Technological Literacy, formed by the National Academy of Engineering and National Research Council, offered "linear steps in the technological design process" [19] displayed in the first column. Similar to the committee's focus on technological literacy for U.S. citizens, the International Technology Education Association (now the International Technology and Engineering Education Association) developed *Standards for Technological Literacy*, which explicitly promoted understanding and applying the design process as essential to technological literacy for all individuals. For example, standard eight addresses the attributes of design suggesting that: "Technological design is a distinctive process with a number of defining characteristics: it is purposeful; it is based on certain requirements; it is systematic, it is iterative; it is creative; and there are many possible solutions" [20]. The technological design process, outlined in these standards, includes activities very similar to those outlined by the Committee on Assessing Technological Literacy, as displayed in the second column.

Table 1. Technological design models

Garmire & Pearson, 2006	ITEA, 2002	NSES, 1996
• Define the problem. • Identify constraints and criteria. • Conduct relevant research. • Brainstorm ideas. • Analyze alternatives (e.g., develop a trade-off matrix). • Identify a potential solution. • Research the potential solution in detail. • Design the potential solution. • Construct a prototype. • Evaluate the prototype against the criteria. • Reiterate if necessary. • Simplify if possible.	• Defining a problem • Brainstorming • Researching and generating ideas • Identifying criteria and specifying constraints • Exploring possibilities • Selecting an approach • Developing a design proposal • Making a model or prototype • Testing and evaluating the design using specifications • Refining the design • Creating or making it • Communicating processes and results	• Identify a problem or design opportunity • Propose designs and choose between alternative solutions • Implement a proposed solution • Evaluate the solution and its consequences • Communicate the problem, process, and solution

As with the *Standards for Technological Literacy*, the *National Science Education Standards* [21] also emphasized the importance of understanding the technological design process for all individuals. The standards outlined abilities for technological design included in the third column.

The design process, from a technological perspective based on the definitions and these models, generally begins with identifying a need or problem. Brainstorming and research are conducted to explore potential solution ideas. An approach is selected by making an informed decision between alternative solutions. Little detail is provided in these models as to how alternative solutions are evaluated and how the solution is implemented, though a constructive process is strongly indicated. The solution is then fabricated and tested. The process ends with communicating the results and testing.

Engineering Design

Engineering design, as opposed to technological design, has been explored in detail by numerous authors. Several introductory textbooks on engineering design line library shelves and many researchers have sought to better understand the engineering design process and its educational implications. This is perhaps due to the perspective, as Koen stated, that design is the essential core of engineering, making it a unique human activity [22]. However, due to the number of individuals writing in this area, there are numerous definitions of engineering design offered. For example, the American Society of Mechanical Engineers suggested:

> Engineering design is the creative process, which leads from the identification of a need to a device or system, which satisfies that need. It is the essential source of all new products. Design is an iterative process involving: a) many alternative approaches to satisfying the need (design concepts), b) multiple and often conflicting requirements and constraints (design criteria), and c) the use of various methods of evaluating and optimizing the alternative concepts (mathematical analysis, computer modeling and simulation, experimental prototyping and testing, and extrapolation from past experience) in order to arrive at the final configuration [23].

Ullman defined engineering design by its outcomes, as:

> The engineering design process centers around four representations used to describe technological problems or solutions. (a) Semantic – verbal or textual explanation of the problem; (b) Graphical – technical drawing of an object; (c) Analytical – mathematical equations utilized in predicting solutions to technological problems; (d) Physical – constructing technological artifacts or physical models for testing and analyzing [24].

The Accreditation Board for Engineering and Technology's definition is that:

> Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs [25].

Obtaining consensus of one clear definition of engineering design is a challenge. Just as with definitions for engineering design, multiple models of engineering design have been offered in the literature. A five stage model suggested by Dym and Little, as outlined in the first column in Table 2, includes: problem definition, conceptual design, preliminary design, detailed design and design communication [26]. Edie, Jenison, Northup and Mikelson presented a shorter design model with six activities outlined in the second column [27]. Another design model is offered by Dhillon, shown in the third column. Dhillon argued that the design process “may simply be described as an imaginative integration of scientific-related information, engineering technology, and marketing for developing a profitable product” [28].

Table 2. Engineering design models

Dym & Little, 2009	Edie, et al., 2008	Dhillon, 1998
• Clarify objectives • Establish metrics for objectives • Identify constraints • Revise client’s problem statement • Establish functions • Establish requirements • Establish means for functions • Generate design alternatives • Refine and apply metrics to design alternatives • Choose a design • Model and analyze chosen design • Test and evaluate chosen design • Refine and optimize chosen design • Assign and fix design details • Document final design	• Define the problem to be solved • Acquire and assemble pertinent data • Identify solution constraints and criteria • Develop alternative solutions • Select a solution based on analysis of alternatives • Communicate the results	• Need recognition • Problem definition • Information gathering • Conceptualization • Evaluation • Communication of design

Upon the review of the definitions and models of engineering, it is evident that there are many key concepts that are common. One key concept, for example, is *systematic*; which is directly used in a number of the engineering design definitions [29, 30] and is implied in other definitions as descriptions of engineers using a systematic approach to developing design solutions. Another key term to describing engineering design is *iteration*. Although engineering design implies a systematic approach, the approach taken in practice is often not linear in nature but iterative [31, 32, 33, 34]. The engineering design process is often an iterative loop whereby the engineer generates a list of questions throughout the multiple stages of the design process. This process causes the engineer to return to the multiple stages of the design process. Engineers are also held accountable to governing rules, regulations, and standards. Engineers must function within defined *constraints* and *criteria* [35, 36, 37]. For example, engineering work has been described as constraint based problem solving [38]. In addition, there are multiple definitions of engineering design that include the term *analysis* or imply a formal analysis process [39, 40, 41].

Comparisons of Design

In reviewing the literature on technology and engineering design there appears to be substantial overlap. From problem definition to idea generation to solution development, both disciplines' approaches to design appear to share commonalities. However, one distinct difference appears to be evident; the end point of the design process. The technology design process models identified for this study culminate with a distinct building or "making" phase with the creation of either a prototype or artifact that is then evaluated [42, 43]. For example, Layton pointed out that with technology design, it is near the end of the design process that designs are translated through techniques into reality, as show in Figure 1 [44]. Perhaps this is due to the discipline's historical focus on artifacts.

Ideas → Detailed Plan → Techniques → Produced Artifacts

Figure 1. Continuum of design

Although there are elements of prototyping in some of the models of engineering design, most of the models presented here suggest that the finished product is a design specification for building and implementing the solution. For example, Dym and Little argued that "the endpoint of a successful design is a set of plans for making the designed device" because "engineers rarely make what they design" [45]. Emphasis is placed on strong communication skills so that the fabrication specifications are clear and transparent so that someone else can build or implement the design. Cross supported this conclusion stating that expectations for engineers in producing a design reside in developing the descriptive aspect of the design specification. The end point of the process is the communication of the specifications of the design, which is the "most essential design activity" [46]. French suggested that ultimately the engineering design process "ends with a set of drawings and other information to enable the thing designed to be made" [47].

sTEm Design

Despite this significant difference, the substantial conceptual overlap between technology and engineering design provides a guide for technology education in the primary, middle, and high schools, as well as implications for collegiate level technology education. As authors of this review, we feel that the history and philosophy of both fields have unique and individual characteristics and strengths. We envision an educational framework for K-16 technology education that represents a synergy between these strengths, titled "sTEm design." The concept of sTEm design is based on the application of mathematic and scientific principles governing our physical world to inform design decisions and presents an opportunity to bring those ideas into tangible reality through the construction of the artifact or implementation of the process. We recognize seven phases in the iterative sTEm design process:

> *Problem definition.* A need or problem must be identified. Research is conducted to better understand the problem and existing solutions. Rationale for change could be the failure of a current product or process or a completely novel concept. This rationale should also justify both the existence of a problem and the lack of an existing acceptable solution. The motivation for allocating resources to meet a need must be clarified. Activities would include identifying constraints and criteria, as well as establishing measures of success.
>
> *Develop potential solutions***.** This phase is characterized by brainstorming and identifying multiple solutions. Each solution may be unique or a slight variation of another solution. Research is conducted to understand why existing solutions are not acceptable. In this phase no idea should be excluded regardless of how impractical, as it may foster another idea which is possible. Analogical reasoning can be a helpful technique to generate multiple solutions including analogies based on nature and other seemingly unrelated concepts [48]. Designs should be conceptually developed such that the designer or design team is prepared to begin refining the list of potential solutions.
>
> *Analyze and select a solution***.** Many potential solutions exist, each with benefits and drawbacks called tradeoffs. Consideration of these attributes requires the designer to balance often conflicting criteria for identifying a best fit solution. Analyzing the solution may take many perspectives from aesthetic to functional. Data should be gathered in a variety of forms from potential users' perspectives to the identification of relevant scientific and mathematics principles. Computer software packages provide powerful tools for visualizing, conducting finite element analysis and modeling the interactions of multiple parts in an assembly. Applying concepts of statics, dynamics, thermodynamics, electrical theory and other relevant scientific principles provides guidance and narrows the potential solution set by illuminating pertinent variables for consideration.
>
> *Optimize a solution***.** With a solution or narrow set of solutions, the problem definition should be purposefully revisited. How can the solution be improved to meet the demands of the problem definition most effectively? As in the analyzing phase, modeling and prototyping will provide insights in challenging aspects of the solution. Costs are considered in terms of the design process (time and resources allocated to developing the design), along with production costs using life cycle analysis. The life cycle analysis should be sensitive to end of use practices – how will this product be disposed? Can its materials be recycled in a closed-loop manufacturing process? Consideration should be given to the environmental, social and political implications of the solution.

*Document design specifications***.** Technical graphics and written documentation should outline a plan for creating a working prototype. The purpose of this document is two-fold. First, it provides a compelling argument that the resources consumed in the fabrication process are justifiable. Second, it allows a team of fabricators to work together in a non-linear fashion on individual elements or subcomponents that will interface together.

*Implement and evaluate***.** The prototype is fabricated based on the design specifications. Modifications to the prototype as required by material or processing limitations should be recognized, documented and confirmed not to substantially impact the form or function of the product or process. An evaluation should be conducted which considers the practical aspects of form and function based on data gathered during implementation of the product or process as a solution. The analysis and optimizing phases provide guidance, but are idealized representations of reality and therefore limited. Careful analysis of the prototype's actual performance can inform the next iteration of analysis and optimization, understanding some error exists and this recognition can serve to calibrate the models guiding development.

*Communicate the problem, process, solution and evaluation results***.** The ability to communicate relevant details about the problem identified, process employed to develop a solution, and evaluation data are essential to document and share intellectual property developed in this process. This documentation serves as a guide in the iterative nature of design wherein the cyclical process continues and designs are refined by more accurate models and understanding.

Teaching sTEm Design

Technology and engineering fields have served differing purposes historically and continue to provide unique contributions to society. Technology education has traditionally had a presence specifically in the K-12 environment for varying purposes in response to societal demands. With the current U.S. climate expressing a sense of urgency to develop its STEM workforce, a revisiting of the "T" and "E" in "STEM" across the K-16 spectrum, is warranted. We recognize value in the *design process* as a defining attribute of technological and engineering education, with distinct educational implications. The seven phase sTEm design model presented here represents an educational framework that builds on the strengths of the engineering design process and technology design process. The problem -based learning literature provides a strong rationale supporting the sTEm design model as an educational framework.

Design in both the technology and engineering disciplines is a complex activity requiring higher-order thinking, "facilitated not primarily by abstract thought but by visual mental imagery and the manipulation of concrete materials" [49]. Specifically, problem-based learning theory offers insight into how educators can deal with the challenge of teaching design as it is "a method of learning in which the learners first encounter a problem followed by a systematic, student-centered enquiry process" [50]. Typically students tackle a loosely-structured, real-world, authentic problem (in this case a design-based problem) by working in small groups to arrive at a solution or resolution to the problem. Students proactively develop self-directed learning skills as they determine how to move forward, the resources to use, and how to acquire and apply new information to formulate and implement a solution. Students work independently and interdependently, determine appropriate solutions, and test their viability.

This pedagogical approach is well suited for sTEm design [51]. Problem-based learning is also organized around authentic, real-world problems. The design problem within a problem -based approach is of crucial importance. The primary element to consider when selecting the problem is determining the underlying principle or the educational purpose of the problem. For higher-order thinking, the problem should "stimulate student activity and engagement" [52], be challenging but not too overwhelming for students, and promote collaborative and authentic learning. Authentic problems translate into higher-order learning because they are meaningful to students. Design-based problems provide that element of authenticity, and within a sTEm framework, provide learning outcomes across the STEM disciplines.

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