Rethinking Accreditation Criteria to focus on Design

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***Abstract*— Accreditation criteria in most countries imply that mathematics and science are the key elements of engineering. This tends to support traditional engineering curricula that emphasise lecture-driven topics in engineering science, such as statics, dynamics, materials, circuits, control, and so on, giving students in four year programs little time to really develop engineering problem solving skills for a world of sustainability and complexity.**

There is a pressing need to redesign engineering curricula around design and problem solving if new engineers are to grapple with complex challenges such as climate change and the need for continuous and relentless innovation. This paper proposes that a good place to start is to reimagine the accreditation criteria for engineering programs.

Keywords—engineering accreditation, engineering design, global challenges, innovation, project-based learning

I. Introduction

Engineering curricula need to change, both to be more inclusive, to attract more women and minorities, and also to graduate the kinds of engineers who will grapple with the complex challenges of the future, not least of which is climate change [1-6].

However, change in engineering curricula is glacially slow, so, how can this be accelerated? What is holding back a profession that relies on the design of 'what has never been'? Why is curriculum change so hard?

This is not a new insight. Karl Smith and others debated just these issues in the European Journal of Engineering Education in 1988 [7]. Nevertheless, this paper takes the view that *design* and related problem solving should be the centre of engineering curricula [8]. As a consequence, programs should be structured around design, whereas programs are usually designed around the acquisition of disciplinary technical and scientific knowledge and procedures, much of which is already available in advanced design software.

The paper first reviews the nature of design and its formalisation in systems engineering. Recent Australian research has demonstrated the centrality of design, investigation and modelling as the key *process skills* of engineering [9, 10] and posed a design-oriented view as underpinning the threshold learning outcomes in Engineering and ICT disciplines [11].

The paper then looks at a range of international accreditation systems and suggests that these accreditation systems perpetuate an old view of engineering, namely the application of science to solve engineering problems. Although engineers do use science and mathematics to predict how their designed systems will perform, engineering is fundamentally a design profession.

Science serves the design process, not the other way around. Science is used as a form of prototyping through numerical modelling of stress, deflection, current, flow, etc., to ensure that these are within permissible limits.

Science helps to answer these questions of system performance. It is less useful in developing an initial, trial configuration of a system. For example, structural mechanics is helpful in determining whether or not a component of a building is of adequate strength and stiffness. However, heuristic design rules are often used to determine the actual component size before the analysis can be completed.

So, what is engineering?

II. Definitions of Engineering

My favourite definition of engineering is this one from Bill Koen [12]:

> *Engineers use heuristics to make the best change in a poorly understood situation within the available resources.*

Koen goes on to demonstrate that science is just one set of many heuristics that are used in engineering. Others include codes of practice, state-of-the-art, engineering software, tacit knowledge of experienced engineers, etc.

The design process (or, formally, systems engineering) provides a systematic approach for engineers to apply Koen's maxim. The *empathise* and *define* stages of design thinking [13] provide several outputs:

i. The best definition of the *poorly understood situation*, a definition that likely continues to evolve
ii. A definition of the *best change* (the system requirements) and
iii. An indication of the available *resources*.

However, it says nothing about *how* an engineer goes about their work in developing a solution to the client needs.

Contrast this definition with others commonly available:

> *Engineers are scientists, inventors, designers, builders and great thinkers. They improve the state of the world, amplify human capability and make people's lives safer and easier.* [14]

> *The work of professional engineers involves the application of advanced skills in analysis and knowledge of science, engineering, technology, management and social responsibility to problem solving and synthesis in new and existing fields.* [15]

> *Engineering is the application of mathematics, as well as scientific, economic, social, and practical knowledge in order to invent, innovate, design, build, maintain, research, and improve structures, machines, tools, systems, components, materials, processes, solutions, and organizations.* [16]

> *An engineer is a person who uses scientific knowledge to design, construct, and maintain engines and machines or structures such as roads, railways, and bridges.* [17]

I suggest that these definitions over-emphasise the role of science and underestimate the systematic design process that engineers use. The next section explores design and its formalisation in systems engineering.

III. DESIGN AND SYSTEMS ENGINEERING

Engineering design has probably been around for 5,000 years, ever since the systematic construction of infrastructure in early civilisations in Egypt, Mesopotamia, China and possibly elsewhere [18]. The basic design process, often now described as *design thinking*, looks like this [13]:

1. *Empathise* with stakeholders
2. *Define* the problem (and its *requirements*)
3. *Ideate* possible solutions
4. *Prototype* one or more solutions
5. *Test* against the requirements

This process is simple enough and general enough to apply to a wide range of problems, not just technical engineering ones.

As the complexity of engineering increased during the 20th century, particularly in telecommunications and defence, systems engineering became established as a more rigorous (and systematic) approach to the design of complex engineered systems [19]:

> *Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle.* [20]

The version of systems engineering on the International Council on Systems Engineering (INCOSE) website, attributed to a consensus of INCOSE Fellows, is the SIMILAR process (Figure 1) [20-22].

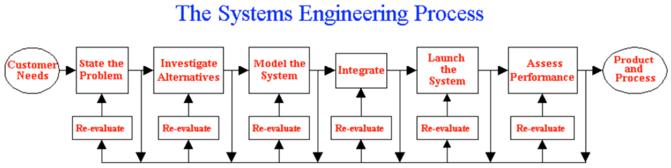

Figure 1. SIMILAR – The (simplified) Systems Engineering Process [20]

Another popular version of the systems engineering process is the V-diagram, which emphasises the importance of testing at all levels of system specification, from Concept of Operations to software and hardware testing (Figure 2) [23]. This could include testing requirements, testing user interface design, testing rough prototypes, modelling, and so on. The aim is to ensure that when the detailed design is underway, the intended outcomes are as clearly defined as possible, eliminating surprises.

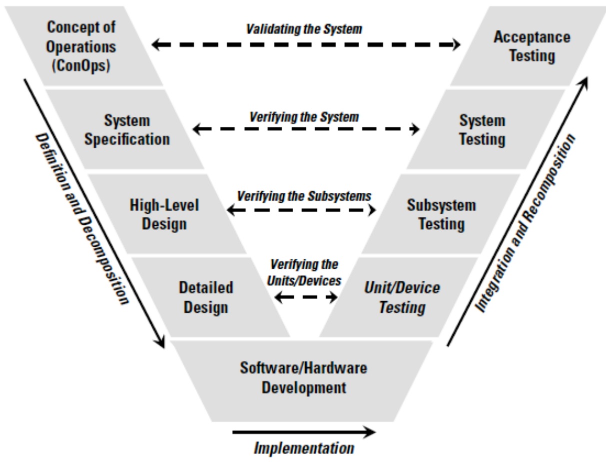

Figure 2. The Systems Engineering V-diagram [23]

IV. TEACHING ENGINEERING AS DESIGN

There is a vast literature on design for aspiring engineers, e.g. Cross [24], Dominick et al [25], Dym [26], Horenstein [27], Petroski [28, 29], Voland [30] as well as a raft of introductory texts that place design in the context of engineering practice, e.g. Stephan et al [31], Dowling et al [32], Dunwoody et al [33], Jensen [34], Kosky et al [35].

Interestingly, however, the coverage of design and the context of engineering practice in these introductory books is quite variable, as shown in Table 1. First year texts tend to be focused on engineering practice, including design, *or* focused on engineering analysis (mathematical modelling of physical phenomena). Only Jensen's text tries to straddle both aspects.

TABLE 1. COVERAGE OF DESIGN IN INTRODUCTORY TEXTS

Book	Design / Practice pages	Maths, Science pages	Design/Total
Stephan	96	480	**17%**
Dowling	700	0	**100%**
Dunwoody	178	0	**100%**
Jensen	222	118	**65%**
Kosky	110	326	**25%**

This supports the notion that many engineering schools continue to teach first the scientific principles and then the design process, perhaps in second year.

In Australia, it is now common to have a design-based subject in first year, often using the EWB Challenge [36] and supported by the Dowling text [32]. Nevertheless, students will sometimes not see design again until third year, depending on the discipline they have chosen.

The question remains, why do many engineering programs persist with this approach – to teach the science first and the design process later? Does this match the research into engineering practice that has emerged in the last 10 years?

V. RESEARCHING ENGINEERING PRACTICE

In 2009-10, the Australian Learning and Teaching Council (now the Office for Learning and Teaching, the OLT) conducted the National Learning and Teaching Academic Standards Project across clusters of university disciplines. The Engineering and ICT cluster's Threshold Learning Outcomes were required to be a high level view of the outcomes required by graduates [11].

These outcomes were derived from extensive industry and academic consultation, including with the two professional bodies, Engineers Australia and the Australian Computer Society and the two Deans' Councils. The national accreditation guidelines as well as international ones and similar projects in other parts of the world, e.g. the Tuning Project [37], were examined and cross-correlated.

Five high level outcomes were proposed [11]:

1. Identify, interpret and analyse *stakeholder needs, establish priorities* and the *goals, constraints and uncertainties* of the system
2. Apply *problem solving, design and decision-making methodologies* to develop components, systems and/or processes to meet the specified requirements
3. Apply *abstraction, mathematics and discipline fundamentals* to analysis, design and operation
4. *Communicate and coordinate* proficiently
5. *Manage* [one's] own time and processes effectively

An overlapping OLT project, Define Your Discipline, explored environmental engineering practice across two years, more than 20 industry meetings and more than 200 participants. The key question was: What do graduates *do* in your company? Participants wrote each task on a sticky note and after generating as many as possible (usually in about 10-15 minutes), each group would cluster the tasks into meaningful groups.

Although we thought that discipline oriented clusters would emerge, e.g. water, soil, air, noise, energy, that was rarely the case. The persistent clusters were: investigation, design, modelling, management, impact assessment, and audit and compliance [9]. Most of these could easily apply to other engineering disciplines, suggesting that these are the high-level process skills that all graduates need. Are we teaching them?

James Trevelyan has compiled an extensive body of research into an excellent text, *The Making of an Expert Engineer* [38]. He points out that engineering requires broader skills than design and problem solving and proposes that the number one activity for engineers is, in fact, *technical coordination*, which requires strong social skills, including collaboration, communication and influencing. Listening, seeing and reading are specific skills that are often neglected. Other skills include informal teaching (of others, on the job), informal leadership, management, financial awareness, and sustainability.

If we are to teach this broad set of skills, then new project-oriented curricula are required. However, I believe that a traditional view is reinforced by our accreditation systems, which continue to emphasise science first, design second, as the next section demonstrates.

VI. OVERVIEW OF ACCREDITATION SYSTEMS

A. International Engineering Alliance (Washington Accord)

The International Engineering Alliance is the umbrella organization that is responsible for the three accreditation accords: Washington (professional engineer), Sydney (engineering technologist) and Dublin (engineering technician).

Its Graduate Attributes and Professional Competencies document [39] emphasises the 'application of science' model of engineering:

> *Engineering involves the purposeful application of mathematical and natural sciences and a body of engineering knowledge, technology and techniques.*

This is further reinforced in section 5.2, Graduate Attribute Profiles. For simplicity, only part of the professional engineer category is shown (Table 2).

However, I contend that a simple reordering and slight rewording of these 4 attributes (out of 12 in total) would present a much clearer view of what it means to be an engineer that would be in line with the outcomes from both the Define Your Discipline project and the Threshold Learning Outcomes (discussed in the previous section). See Table 3.

B. ABET

The Accreditation Board for Engineering and Technology (ABET) in the US, is well known for its a-k requirements for student outcomes (Table 4) …

… which, I believe, would be better sequenced as shown in Table 5, with *additions in italics*. This sequence better matches how industry would rate these capabilities, as revealed in Sally Male's investigation of generic competencies for engineers [40].

TABLE 2. WASHINGTON ACCORD OUTCOMES

Differentiating Characteristic	for Washington Accord Graduate
Engineering Knowledge:	WA1: Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to the solution of complex engineering problems.
Problem Analysis (Complexity of analysis)	WA2: Identify, formulate, research literature and analyse complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences.
Design/ development of solutions: Breadth and uniqueness of engineering problems	WA3: Design solutions for complex engineering problems and design systems, components or processes that meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations.
Investigation: Breadth and depth of investigation and experimentation	WA4: Conduct investigations of complex problems using research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions.

TABLE 3. MODIFIED SEQUENCE OF WASHINGTON ACCORD OUTCOMES

Differentiating Characteristic	for Washington Accord Graduate
Investigation: Breadth and depth of investigation and experimentation	WA4: Conduct investigations of complex problems *by engaging with stakeholders*, also using research-based knowledge and research methods … **The key skill here is to ask good questions to identify: *what problem are we solving?***
Problem Analysis (Complexity of analysis)	WA2: Identify, formulate, research literature and analyse complex engineering problems reaching substantiated conclusions … **This could easily be combined with WA4**
Design/ development of solutions: Breadth and uniqueness of engineering problems	WA3: Design solutions for complex engineering problems and design systems, components or processes that meet specified needs with appropriate consideration for public health and safety, cultural, societal, and environmental considerations.
Engineering Knowledge:	WA1: Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to the solution of complex engineering problems. **This places scientific knowledge where it belongs, namely in the prototype and test phases**

TABLE 4. ABET A-K REQUIREMENTS

a)	an ability to apply knowledge of mathematics, science, and engineering
b)	an ability to design and conduct experiments, as well as to analyze and interpret data
c)	an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
d)	an ability to function on multidisciplinary teams
e)	an ability to identify, formulate, and solve engineering problems
f)	an understanding of professional and ethical responsibility
g)	an ability to communicate effectively
h)	the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
i)	a recognition of the need for, and an ability to engage in life-long learning
j)	a knowledge of contemporary issues
k)	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

TABLE 5. RESEQUENCED ABET REQUIREMENTS

a)	an ability to identify, formulate, and solve engineering problems, *including the ability to engage with internal and external stakeholders*
b)	an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
c)	the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
d)	a knowledge of contemporary issues
e)	an understanding of professional and ethical responsibility
f)	an ability to function on multidisciplinary teams
g)	an ability to communicate effectively
h)	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.
i)	an ability to apply knowledge of mathematics, science, and engineering
j)	an ability to design and conduct experiments, as well as to analyze and interpret data
k)	a recognition of the need for, and an ability to engage in life-long learning

C. Engineers Australia

Engineers Australia has a similar list of outcomes, which also privileges the knowledge of science and mathematics over design (Table 6) [41].

Rearranging provides a view of engineering that is more in tune with engineer as design-oriented problem solver (Table 7). However, the outcomes are still not worded in a way that would inform or inspire a prospective student and their parents. The modified ABET requirements are more appealing from the novice point of view (in my opinion).

TABLE 6. ENGINEERS AUSTRALIA'S STAGE 1 COMPETENCIES FOR PROFESSIONAL ENGINEER

1. KNOWLEDGE AND SKILL BASE
   - 1.1. Comprehensive, theory based understanding of the underpinning natural and physical sciences and the engineering fundamentals applicable to the engineering discipline.
   - 1.2. Conceptual understanding of the mathematics, numerical analysis, statistics, and computer and information sciences which underpin the engineering discipline.
   - 1.3. In-depth understanding of specialist bodies of knowledge within the engineering discipline.
   - 1.4. Discernment of knowledge development and research directions within the engineering discipline.
   - 1.5. Knowledge of engineering design practice and contextual factors impacting the engineering discipline.
   - 1.6. Understanding of the scope, principles, norms, accountabilities and bounds of sustainable engineering practice in the specific discipline.
2. ENGINEERING APPLICATION ABILITY
   - 2.1. Application of established engineering methods to complex engineering problem solving.
   - 2.2. Fluent application of engineering techniques, tools and resources.
   - 2.3. Application of systematic engineering synthesis and design processes.
   - 2.4. Application of systematic approaches to the conduct and management of engineering projects.
3. PROFESSIONAL AND PERSONAL ATTRIBUTES
   - 3.1. Ethical conduct and professional accountability.
   - 3.2. Effective oral and written communication in professional and lay domains.
   - 3.3. Creative, innovative and pro-active demeanour.
   - 3.4. Professional use and management of information.
   - 3.5. Orderly management of self, and professional conduct.
   - 3.6. Effective team membership and team leadership.

TABLE 7. ENGINEERS AUSTRALIA'S STAGE 1 COMPETENCIES RESEQUENCED

1. ENGINEERING APPLICATION ABILITY
   - 1.1. Application of established engineering methods to complex engineering problem solving.
   - 1.2. Fluent application of engineering techniques, tools and resources.
   - 1.3. Application of systematic engineering synthesis and design processes.
   - 1.4. Application of systematic approaches to the conduct and management of engineering projects.
2. PROFESSIONAL AND PERSONAL ATTRIBUTES
   - 2.1. Ethical conduct and professional accountability.
   - 2.2. Effective oral and written communication in professional and lay domains.
   - 2.3. Creative, innovative and pro-active demeanour.
   - 2.4. Professional use and management of information.
   - 2.5. Orderly management of self, and professional conduct.
   - 2.6. Effective team membership and team leadership.
3. KNOWLEDGE AND SKILL BASE
   - 3.1. Comprehensive, theory based understanding of the underpinning natural and physical sciences and the engineering fundamentals applicable to the engineering discipline.
   - 3.2. Conceptual understanding of the mathematics, numerical analysis, statistics, and computer and information sciences which underpin the engineering discipline.
   - 3.3. In-depth understanding of specialist bodies of knowledge within the engineering discipline.
   - 3.4. Discernment of knowledge development and research directions within the engineering discipline.
   - 3.5. Knowledge of engineering design practice and contextual factors impacting the engineering discipline.
   - 3.6. Understanding of the scope, principles, norms, accountabilities and bounds of sustainable engineering practice in the specific discipline.

VII. DESIGN-ORIENTED CURRICULA

Project-oriented curricula are not new, though they are also not common across the world. The trailblazer was likely Aalborg University in Denmark (from 1974) and it continues to attract those interested in applying problem-based learning approaches within an engineering project-oriented context [42, 43]. Other examples include Olin College in Boston and Iron Range Engineering [44] as well as individual programs in several universities in Australia (UQ, CQU, RMIT, Monash, Deakin, VU).

Nevertheless, making change and maintaining change are both difficult processes [45]. Given that accreditation is the one systematic quality improvement process that most engineering schools engage in, this might be a useful place to start to remake the image of engineering from the application of science to systematic (and quantitative) design.

In that process, we might also reimagine engineering as a gender-inclusive discipline, in order to attract more women into the profession.

VIII. CONCLUSIONS

Engineering programs around the world continue to be dominated by learning the disciplinary fundamentals, with engineering design often treated as an application of theory, rather than a skill in its own right – a means of grappling with complexity using systems engineering methods.

This paper has reviewed three widely used accreditation systems and noted that each continues to emphasise knowledge of science and mathematics before knowledge of design and problem solving. However, research into engineering practice indicates quite the opposite – engineers spend little time solving technical problems in detail and much more of their time performing what James Trevelyan calls technical coordination [38].

This is not to suggest that the accreditation systems are to blame, because the form of our curricula predate the accreditation guidelines. However, I suggest that the guidelines are not helpful in encouraging universities to rethink their curricula in line with the many international reviews that have been published in the last 15 years.

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