A New Kind of Engineer: Incorporating Complexity, Uncertainty and Ethics as Bases for EESD

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Abstract

After a decade and a half of Engineering Education for Sustainable Development (EESD), a view has emerged around the need for programmes to go beyond incorporating SD/sustainability as mere *'add on'* material or elective modules to already overcrowded curricula, to instead acting as a *'leading principle for curricula'* whereby *'engineering universities [would] renew their culture emphasizing commitment to contribute to society, solidarity, openness and creativity'* thus *'making engineering education creative, effective, societally engaged, open to other disciplines and really enjoyable'* (Mulder *et al.*, 2012). This, as Mulder *et al.* (2012) note, *'implies that an engineer should understand the complexities of the societal setting in which he/she is developing solutions, and the complexities of making short term improvements that fit into a long term SD path.'*

This paper reflects on how a recently developed first year module taught to all engineering undergraduates at University College Cork, Ireland, has attempted to engage students with issues of ethics, complexity, inherent uncertainty and risk as foundational bases for productively engaging with SD/sustainability (Byrne, 2012; 2012a). It does this through considering the results of targeted post module student feedback as well as student assessment output, taking (engineering) educational as well as sociological perspectives, finding some promising though mixed results.

The module was developed and delivered by the lead author with the aim of providing a suitable basis from which students could, through the rest of their programme, be afforded the potential to develop into fit-for-purpose engineering graduates capable of contextualising and dealing with contemporary wicked 21st century problems around unsustainability from local through global levels. The module incorporates material on engineering philosophy, the role of engineering in society, micro and macro ethical frameworks, risk and uncertainty in complex and wicked problems, and concepts around the new engineer and post-normal science. Assessment includes groups addressing respective wicked problems with subsequent presentations to peers and staff.

1 Introduction

There is a realisation that what has been called a 'new engineer' is required for fit for purpose 21st century engineering in order to address the attendant challenges and crises that face contemporary society and a requirement for transformational change towards a sustainable construct (Beder,1998). The new engineer is a conception of a professional as one who strives to develop and use their critical analytical functions, recognises that values and ethics are inherent in all engineering practice, leaves hubristic illusions of control aside and embraces context, complexity, inherent uncertainty and risk (Bucciarelli, 2008). It recognises the *'deep sociotechnical complexities that are often at the heart of [engineering] "Grand Challenges."'* while making *'explicit the social and ethical responsibilities of engineers'* (Herkert & Banks, 2012). The new engineer thus recognises the value of scientific and technological approaches in relation to contemporary societal challenges, but acknowledges that technocentric approaches alone are incapable of achieving progress towards sustainable outcomes among inter-related complex social, techno-economic and ecological systems (Conlon, 2008); these must be supplemented by contingent context dependent approaches complimented by experiential and local knowledge and intuition, rather than through a reductionist approach characterised by technological determinism.

This is a view which is compatible with many of the conclusions which have emerged across the domain of Engineering Education for Sustainable Development (EESD) over the past decade and a half. It also aligns with contemporary directions in the sociology of sustainable development [e.g. Baillie *et al.*, 2013] and with education and pedagogical theory [e.g. Boud, 2000]. Much EESD literature proposes the incorporation of sustainability within and across engineering programmes as a *'leading principle for curricula'* to elicit a broader conception of the engineer (as opposed to incorporating content merely as *'add on'* material to an already overcrowded curriculum) (Mulder *et al.*, 2012).

This paper reflects on the experiences of a first year module on a (four year) undergraduate engineering programme at University College Cork (UCC), Ireland which seeks to help facilitate the development of a fit for purpose 21st century engineer. It is informed by both contemporary sociological and engineering education/EESD perspectives.

2 Module Description

This study is based on a first year module taken by all engineering students across four engineering programmes at UCC during their first study period at university. The module, entitled, Professional Engineering Communication and Ethics (code: PE1006), was conceived and drawn up as part of a curriculum review and restructuring exercise across the School of Engineering which saw the introduction of an almost common first year programme among all four UCC engineering programmes (Civil & Environmental, Electrical & Electronic, Energy and Process & Chemical) from 2011-2012. The module was developed by a small team of engineering academics within the School of Engineering and includes contributions from three academics across the school, including the lead author who is module coordinator and teaches half the module.

The part of the module objective taught by the lead author as per the university's 2012-2013 Book of Modules related to *'..developing an appreciation of professional ethics through application in complex problems and case studies.'* The corresponding learning outcomes are to:

- Relate professional engineering practice to the ethics and ethos of the profession and the role of engineering in society
- Understand the nature of complex wicked problems and apply appropriate strategies for resolving such problems.

Contact time with the class by the lead author was 24 hours, comprising 12 teaching hours, 8 hours of design/tutorial sessions and 4 hours of student assignment presentations around the following topics:

- Role of engineering in society
- Wicked problems
- Philosophy of engineering [historical and current philosophies and trends]
- Professional engineering ethics and ethos
- Micro and macro ethical frameworks
- Complex problems; risk and uncertainty
- The new engineer and post-normal science

The principal assessment for this part of the module comprised a group assignment on a 'wicked problem'. This comprised forty per cent of the overall module grade; all module marks were allocated to various elements of continuous assessment. The wicked problem assignment aims to reflect the material covered in the module and the reality that artificial, oversimplified, well defined problems and case studies often neglect *'the social complexities of engineering practice'* (Bucciarelli, 2008).

The term 'wicked problems' was coined by Horst Rittel and Melvin Webber in a seminal paper where they described these as messy problems where there is potential for disagreement in terms of their framing as well as around any proposed solutions (Rittel and Webber, 1973). Indeed, they suggest that *'it makes no sense to talk about "optimal solutions"'* as *'there are no "solutions" in the sense of* *definitive and objective answers.'* Nor can there be any test to the 'solution' to a wicked problem, except through a pragmatic approach where options are tried and experiential knowledge is gained. As such, wicked problems are more than just purely technical problems; they involve some societal aspect or interaction with people. Technical solutions alone are therefore usually not sufficient in tackling wicked problems; non-technical and policy/value based approaches are required also. Tackling them also requires collaboration, usually between stakeholders with different backgrounds, disciplines and experience; to help understand each other's positions or 'object worldviews' well enough to have intelligent dialogue about the different interpretations of the problem. This requires a new type of engineer, one which demonstrates *'increased reflexivity and broadened participation in how engineers define problems and attempt to solve them'* and one who is equipped to *'to deal with the dimensions of these challenges that are considered outside the "technical" realm'* (Cech, 2012).

Students are assigned alphabetically to groups of five and are invited to collectively choose a wicked problem from a list of twenty six. These include for example, problems on energy provision, water quality and provision, nanotechnology and nano-particles, traffic, sea level/flood protection, electronics waste, plastics, hazardous waste, food production, atmospheric carbon levels, local flooding events, chemical plant safety, nuclear power, road safety, computers and artificial intelligence and electric power transmission.

They are required to investigate the problem, consider the perspectives of different stakeholders and see how each might contribute to both the problem specification/description/framing and then how they might contribute to a response or responses. Groups are also required to nominate a designated person whose formal role is to 'institutionalize doubt', a 'yes, but…' person who must act as a 'devil's advocate' and hence speak up, point out problems, critique suggestions, generate discussion, get the group to consider how worst case scenarios might be dealt with or consider different perspectives or (perhaps larger) windows on the world.

Groups are then invited to produce posters on their work and prepare a short (7 minute) presentation to peers and the lecturing team. The actual presenter was drawn at random from the team of five just before the presentation and all the team members then answer questions in a short question and answer session following the presentation.

The module and assessment of this (part of the) module were thus designed to facilitate the development of critical thinking, as well as a degree of understanding and comfort in handling complexity and uncertainty and the ethical dimensions of engineering practice through this introductory engineering module. This also facilitates the adaptation of a broader conception of the role of engineering necessary for a meaningful engagement with EESD. This module therefore acts as a complimentary basis for a module on 'Sustainability in Process Engineering' that third year students of the process and chemical engineering programme subsequently take, also given by the main author.

3 Student Learning Experiences and Feedback

The student learning experience and success in meeting the goals of the module during 2012-2013 were assessed via a number of approaches:

- A dedicated anonymous post module reflective survey.
- Module feedback administered anonymously by the university's Quality Promotion Unit.
- Student material presented as part of the wicked problem assignment.

3.1 Reflective Survey

This survey was carried out after the module's completion. Of 125 students taking the module during 2012-2013, 73 responded, representing a 58% response rate. Part 1 of the survey sought to ascertain to what extent students embraced ideas presented in the module. To do this, students were asked to which of two statements they most closely agreed with from each of seven statement pairs. The first of each pair represents a viewpoint which aligns with the dominant hubristic societal (reductionist and deterministic) paradigm which has characterised modern engineering (Riley, 2008; Herkert & Banks, 2012). The latter statement more closely aligns with a paradigm of complexity, inherent uncertainty and associated humility which permeates this part of the module. Students were also asked to reflect and indicate whether (in their opinions, retrospectively) the statement they supported represents a change from the view they held *before* they took the module. Of the 73 respondents, 53 indicated whether or not the module helped precipitate a change in their outlook; the remainder did not indicate either way.

Table 1: PE1006 Professional Engineering Communication and Ethics Reflective Survey (2012-13)

Tick whichever statement you agree most closely with:

Because Engineers like to gather the **facts** from which the **truth** can be **logically determined**, they are best positioned to solve many problems.	6 (0% change (0/5))
The **'truth'** cannot be achieved through facts and logic alone; in fact, there are **many possible legitimate truths within given frameworks** – e.g. different disciplines hold different perspectives and hence different truths.	67 (25% change (12/48))
Engineering is largely (or exclusively) a **value free** endeavour.	6 (0% change (0/2))
Values are inherent in all **engineering** practice.	67 (16% change (8/51))
Improving efficiency is **the key feature** of **good engineering** – continually increasing both technological efficiency and human productivity towards system optimisation.	27 (5% change (1/20))
While **efficiency** is important for engineering, a sole focus on improving efficiency represents **poor engineering practice,** as it **reduces system resilience and redundancy** while **increasing tight coupling and risk**	46 (61% change (20/33))
Basic scientific research is required as a **precursor** to **technological innovation**.* *(*e.g. as practised by engineers)*	20 (0% change (0/16))
Technological innovation* is often largely **experiential** and **pragmatic** and emanates from **ideas** and **creativity**. **Basic scientific knowledge**, while potentially useful to this process is **not necessarily a prerequisite**. *(*e.g. as practised by engineers)*	53 (32% change (12/37))
Engineers should be considered **value neutral 'guns for hire'** or 'paid hands'.	8 (17% change (1/6))
Engineers should be **committed to social good**, thus bestowing **privilege** in some ways, while also conferring a level of **responsibility** for their work and its consequences.	65 (21% change (10/47))
Risk can be represented by **objectively quantifying** the likelihood of an incident occurring.	21 (13% change (2/16))
Risk is **a social phenomenon** and is **culturally constructed**; the likelihood of an incident occurring is inherently subjective and thus in turn influences both the approach taken towards a risk and the risk level.	51 (56% change (20/36))
When the **general public oppose engineering projects**, it is often due to **scientific or technical ignorance**. It is therefore a key role of the **engineer** as **experts** to better inform the public; we need to **improve our communications**.	22 (13% change (2/16))
When the **general public oppose engineering projects**, it is often **not** due to inherent scientific or technical ignorance, but because the project **conflicts with inherent values**, for example around ideas of wellbeing, community, acceptable risk. This requires a **broader** more participatory **conception of engineering** (the **'new' engineer**).	50 (25% change (9/36))

Results of part 1 of the survey are presented in Table 1. A striking aspect of the results is the strong support for the second statement across each of the pairs of statements. In particular there was very strong support for the contention that different possible legitimate truths can exist within different frameworks, that values are inherent in engineers practice and that engineers should be committed to social good. Intellectually at least, it would, appear there is strong support among students of the module for the concept of the new engineer and a strong sense of social responsibility prevalent among first year engineers. The module itself appears to have helped reinforce this significantly – as might be expected, given the tendency for intrinsic (greater than self) values for example, to be strengthened by exposure to them, and for the opposite to occur when extrinsic (selfish) values are portrayed (WWF, 2010).

This is in fact strongest for the pair which generated most division; initially most students would have agreed that efficiency was *'the key feature to good engineering'*, though having taken the module some 20 of the 53 who indicated whether they had changed their mind of not did change their mind, so that after the module about five eights of those who responded were willing to adopt the more nuanced view that while efficiency is important for engineering practice, a singular emphasis on this particular ratio means that system resilience and redundancy is reduced while tight coupling and risk increases (essentially a singular focus on efficiency inhibits system sustainability (Ulanowicz, 2009)). There were also large shifts in students perceptions of risk, regarding it more as a social phenomenon (as opposed to objectively quantifiable entity), on the basis for technological innovation, on truth as a function of frameworks and on public opinion being primarily based on inherent values rather than scientific ignorance. Taken together, these perceptions appear to indicate that students generally show a very positive disposition towards the ideas associated with the 'new engineer'. On the other hand, in absolute terms very few students (less than three in all cases) claimed to have changed their minds towards the more positivistic statements.

A couple of points are pertinent in considering student responses. The module has no end of term exams (only continuous assessment exercises) and questionnaires were administered anonymously (through in-class hard copies). Therefore, there was no compulsion on students to be coerced into new or different ways of thinking or to provide answers that they might think would impress the lecturer. On the other hand, the reality of the power structure inherent in the system, whereby the lecturer may be viewed as a sort of fount of definitive knowledge is unavoidable. Even if/when other lecturers propose other potentially antagonising versions of 'definitive knowledge', this may be worn lightly by students as they can pragmatically flip-flop between different conceptions of reality, given the structure of their programme is generally reductionist in the sense that it is comprised a number of separate modules which combine to produce the degree, and apart from perhaps final year capstone design or research projects, does not either promote or require an integrative approach to learning and teaching.

The second part of the survey was designed to see how students understood what had been covered in the module and see how their conception of the role of an engineer might now be having just completed the module. It thus asked the following pair of open ended questions (followed by a selection of responses):

1. What is the single most relevant thing you have learned as part of this part of the module PE1006?

- *That ethics and values are an inherent part of engineering and cannot be ignored. The concept of the 'new engineer'.*
- *Values are essential in the lives of engineers. Choices that engineers make cannot be based on scientific knowledge alone but also based on social, ethical and economic values.*
- *Engineering isn't just about thinking in a linear, mathematical way about problems. It must take social (and other) aspects into consideration.*
- *I have learned to look at problems in many different ways i.e. there are very few problems with one specific solution. Each solution has problems within.*
- *How risk can be thought of as a social phenomenon and how a perceived risk can affect people's actions.*
- *A wider range of thinking and consideration when seeking solutions to problems. There is no perfect solution to most engineering obstacles.*

2. What is the role of the engineer?

- *Help solve problems in society by innovative solutions, while taking into consideration society and likely reactions to such a solution.*
- *To utilise the resources available to man for the betterment of mankind.*
- *To provide a clear and logical solution to a posed problem.*

- *The role of the engineer is to use the forces of nature to better human life.*
- *Apply technical knowledge to solve social problems. While engineers work largely in a technical; context there is also a social responsibility.*
- *To improve quality of life through science and technology, to innovate to find answers to modern day problems and to bring solutions to life.*

The responses to question 1 indicate that students took on board and saw as relevant many of the concepts covered as part of the module on issues around values, ethics, indeterminacy, risk and the relationship between social and technical aspects of engineering. Question 2 on the role of the engineer elicited a more mixed response however. Students appeared to struggle with incorporating the concepts they expressed in the previous question and in the earlier part of the survey into their conception of the role of the engineer. The responses shown above, which are representative of those presented, reverts to a conception of engineering that either mirrors the traditional self-perception of the engineer (in accord with the dominant paradigm) or is some muddled version of this, overlain with some of the conflicting ideas presented in the module. Thus, we get an engineer who is obliged to coerce all (sorts of) problems into a framework which will allow these to be heroically 'solved' using a toolbox which contains only technological tools: *'apply technical knowledge to solve social problems'*. A hubristic notion that engineers can singlehandedly solve problems – even 'social' ones, and can do so through science and technology appears to be prevalent. Moreover echoes of the modern Cartesian philosophy *("It is possible to reach a kind of knowledge which will be of the utmost use to men and thereby make ourselves the lords and possessors of nature"* (Descartes, 1638)) abound: *'utilise the resources available to man for the betterment of mankind'; 'use the forces of nature to better human life'*. Only the first response, which presents the role of the engineer in a broader, and more tentative and contingent light, appears to begin to grasp the import of the 'new engineer'. There thus appears to be a discontinuity of sorts; while formative engineers are prepared to intellectually accept a new and broader conception of engineering, they struggle to meaningfully apply this in terms or how this might affect the role of the engineer and in the practical application of engineering.

3.2 Module Feedback

Feedback on the principal author's section of the module was garnered independently through UCC's Quality Promotion Unit (QPU) following module completion. This electronic survey elicited a response rate of 48% (60/125). One of the questions on this survey related to how this part of the module stimulated students' thinking. Three quarters of respondents agreed that the module precipitated stimulation of their thinking 'above average) (Table 2). This result aligns with the relatively high proportion of students who claimed to have changed their perspectives via the module.

Table 2: Online anonymous survey on PE1006 (E. Byrne's section) (n =125)

	Excellent	**Above average**	**Average**	**Below average**
The stimulation to my thinking provided by this lecturer is:	21 (35%)	23 (39%)	11 (18%)	5 (8%)

3.3 Student material created for the wicked problem assignment

The wicked problem assignment afforded students the opportunity to demonstrate the extent to which they could incorporate in a practical way, many of the aspects covered in the module, and to which they generally claimed to ascribe. However, this proved to be a difficult exercise. One student alluded to this on the QPU survey when they commented: *'Very interesting, but also complex. It is just difficult to figure out how to EXACTLY start approaching wicked problems, but the principles and methods were made clear enough'*. The student presentations appeared to reflect this as students struggled to integrate the concepts they claimed to uphold in addressing real life wicked problems. This resulted in a general lack of coherence and contradictory proposals, while in most cases groups ultimately proposed traditional reductionist 'solutions' to their respective problems, typically characterised by a singular drive towards ever greater efficiency. For example, one group looked at the problem of traffic and proposed that it could be solved by bigger, straighter and 'better' designed roads through signage, road markings, surface quality, flyovers, etc. At the same time, they recognised in their presentation that this approach does not look at 'the bigger picture' and may ultimately lead to increased traffic volumes. However, they offered no further or alternative proposals or insights.

4 Reflection

A constructivist approach to learning supports the idea that it represents a personal journey whereby students can be helped to (re)construct their conceptions of reality. In this context, engineers can be exposed to opportunities to explicitly (re)envisage their roles and responsibilities and some of the dominant 'truths' that underlie engineering practice and contemporary society around complexity, determinacy/uncertainty and values/ethics, for example, and will respond positively to such opportunities. However, even though people may accept certain values, paradigms or worldviews intellectually, this does not necessarily imply they will change their behaviour instantaneously, or even at all. There may be other conflicting values that are stronger and/or structural barriers to change in a wholly interconnected society (WWF, 2010). Peer pressure and groupthink too are extremely powerful human drivers. The all-pervasive dominant paradigm (throughout society and other parts of the curriculum) should not be underestimated, and initial change is usually slow and incremental. However, complexity theory and Kuhn's thesis (Kuhn, 1963) suggest that while change comes dripping slowly at first, ultimately old paradigms experience catastrophic collapse to be replaced by a new reality.

The experience with this module is that while students are willing to explicitly accept the outcomes of a complexity based paradigm, and while they recognise both the coverage of such in the module and importance professionally of understanding concepts such as context, uncertainty, complexity and ethical sensitivity (Byrne, 2012a), nevertheless they struggle to implement this in practice. Students clearly struggled to 'join the dots' when faced with the key but difficult task of practical implementation. This is perhaps unsurprising as when faced with a challenge of implementation in any learning process, it is easier to revert to type (i.e. previously held, more deeply embedded constructs of reality) when faced with a new and significant challenge. Moreover behavioural change in response to changes in people's environmental circumstances is typically non-linear, often following fractal-like 'zigzag course' (Hernes, 2012). On reflection, the principal author will attempt to address this during future module iterations by taking an example previously made presentation in class – such as the traffic example – and inviting students themselves to critique it and in doing so, to reflect on how broader contextualised approaches might be applied. This should precipitate students reflecting on the social complexities of traffic such as for example, urban and suburban planning, the status of pedestrians, cyclist and public transport as well as other broader issues such as health and well-being, obesity, energy and fuel consumption. It might be useful to ask too what are the ethical issues around their selected wicked problems as part of the assignment and hence to facilitate reflection more generally on *'what the social and ethical commitments of engineering are and ought to be'* (Herkert and Banks, 2012).

5 Conclusion

A new kind of engineer is required if engineering is to be fit-for-purpose to address 21st century sustainability related challenges. Such an engineer challenges current paradigmatic reductionist thinking and requires a broader more contingent view of the role and responsibilities of the profession. The self-perception of such an engineer goes well beyond that whose only tool in their toolbox is technology and whose default approach is increased efficiency. Communications and transportation system design for example, need to utilise technology efficiently but a one dimensional engineer who cannot relate to the social implications is one who merely serves to contribute to deeper and more widespread 'unintended' consequential problems associated with and driven by emergent technologies. A key intervention point in the precipitation of a broader fit-for-purpose profession is through its formative professional education. Undergraduate engineers require exposure to contemporary knowledge and research around the nature of complexity, indeterminate uncertainty and ethics to provide them with the opportunities to be equipped with the necessary tools to embrace and facilitate meaningful societal transformation, in concert with other disciplines and extended peer groups. The current work examined a module which has sought to help develop such an approach, reflected on the challenges that arose, and proposed some suggestions.

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