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Development of contemporary engineering graduate attributes through open-ended problems and activities

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Abstract

The engineering graduate of today will engage in a career which will span the middle of the twenty first century, and beyond. They will work in a world which is increasingly more complex and uncertain than at any time before. This will require an integrated combination of technical knowledge and transferable skills and values, to a greater extent than ever before. This paper highlights the need for the contemporary engineering graduate to develop capacity to deal with increased uncertainty and complexity. It seeks to demonstrate how this can be achieved through developing key graduate attributes. These attributes may be promoted through suitable exposure to progressively more open-ended problems and activities across the programme. A number of exemplars are provided from two European chemical engineering programmes.

Keywords

Transferable skills and values, employability, uncertainty, complexity, sustainability, open-ended problems

1. Introduction

The obligations and opportunities for chemical engineering in an unsustainable world were speculated upon over a decade ago, where it was argued that sustainability should act as a contextual lens for the formative education of chemical engineers (Byrne and Fitzpatrick, 2009). Many of the proposed ideas have been mainstreamed and developed, including active engagement with other disciplines and with wider society, in the context of increasingly elevated levels of societal and technological complexity and interconnection, and resultant graduate imperatives for handling and embracing uncertainty (Knight and Yorke, 2006; Byrne, 2012; Byrne and Mullally, 2014; Gallego-Schmid et al., 2017; Lozano et al., 2017).

This paper seeks to provide value to the education of engineers (citing examples from the authors' discipline of chemical engineering) in two respects: firstly, as a contribution to the broader conversation of the required attributes for the contemporary engineering graduate, in the context of a looming sustainability crisis, and secondly, by providing some exemplars from two chemical engineering programmes of open-ended activities being implemented in two universities, aimed at developing key graduate transferable skills, professional values, and sustainability attributes, as necessary compliments to the basic requirement of developing sound technical capability.

The chemical manufacturing industry has been subject of accusations of overexploitation of natural resources leading to air, water and land pollution (Hall and Howe, 2010). From this perspective, the way that chemical engineers practice, embrace and implement sustainability entails a paradigm shift in how we conceive and practice chemical engineering and its education. This entails recognising and dealing with open-endedness across the ecologically and economically bounded socio-technical systems and processes we design and engage with. It also requires authentic productive engagement with other professions and with communities.

In terms of engineering education, this imperative has been progressed through accreditation guidelines and requirements and by emerging and contemporary pedagogical best practice (Sterling at al., 2013; Kezar et al., 2018; Tassone et al., 2018). For example, the UK based Institution of Chemical Engineers' (IChemE) policy roadmap Chemical Engineering Matters (IChemE, 2016) unequivocally proclaims that 'IChemE is an advocate for solutions that will support a safer and more sustainable world', while exhorting educators to produce 'a confident and outward-looking international chemical engineering community that will play its part fully in building a more sustainable future.' In a similar way, according to the Spanish

Agency for Quality Assessment and Accreditation (ANECA, 2019), the objective of chemical engineering education must be to form professionals 'in terms of quality, safety, economy, rational and efficient use of natural resources and conservation of the environment, complying with the ethical code of the profession'.

In the case of engineering, as a broad-based practical and practitioner based profession, it is important to continually adapt and respond to constant evolution of professional imperatives and to educational and societal trends and contexts, in order to produce graduates who are continually in touch with the real world (Abbas and Romagnoli, 2007). Thus, the contemporary engineer requires competences not just in the core competences or 'knowledge' domain ('the data base of the professional engineer'), but also in that of transferable 'skills' (experimentation, analysis, synthesis, communication, leadership, teamwork), and 'attitudes' (professional values, ethical frameworks) (Rugarcia et al., 2000; Jansen et al., 2008). This integrated model of knowledge, skills and attitudes (or values) is a long-established construct within the broader educational literature (Dill, 1990; Chong and Cheah, 2009; Baartman and De Bruijn 2011). Indeed, while the latter professional 'values' domain cross cuts the other two, nevertheless it is here where engineering education has traditionally been found wanting. In the context of emerging and emergent twenty first century challenges, this is of vital importance in the education of the fit-for-purpose engineer.

The successful incorporation of these components into the curriculum requires new, more student-centred teaching and learning approaches relative to the traditional. Specifically, this entails the education of engineers capable of making decisions which routinely take into account the social, ethical, and moral consequences of those decisions. This includes the deployment of a sustainability ethic throughout one's practice. In this way, the expansive role that engineers can (and ought) play must increase, not just in addressing complex problems with societal and natural/ecological dimensions, but also in the very *framing* of such problems. This implies the development of a profession which is both more satisfactory for practitioners and more attractive for potential recruits.

A critical learning goal among transferable skills in engineering education is to facilitate the development of independent learners. In practice however, traditionally engineering programmes have promoted students as dependent learners, whereby relevant fundamental knowledge can be obtained from texts, online repositories and teachers (Hamzaha, et al., 2012). Recent research suggests that undergraduates are unable to appreciate the transferable skills that employers are seeking without them being prompted (Hill et at., 2018), much less the importance of attitudes, or the normative, values-based dimension of engineering practice.

Learning based on open-ended problems or activities is not new. In fact, there are a large number of papers dealing with this topic, although not so many that focus on industrial practice incorporating sustainable development, and scarcely any aimed at developing key graduate transferable skills, professional values and sustainability attributes. The literature on open-ended problems and activities appears mainly within Problem-Based Learning (PBL), Cooperative Learning (CL) approaches (Hamida et al., 2012; Surif et al, 2014; Balan et al., 2019; Sadikina et al, 2020), Design-Based Learning (DBL) and Project-Based Learning approaches (Chandrasekaran et al., 2012; Gómez Puente et al., 2017; Huang et al., 2020), laboratory-based modules (Chen et al, 2016; Ali et al, 2016) or laboratories made for specific purposes (Mahmoud et al, 2020), through the interactive use of computers with suitable software (Taylor, 1985), internet resources (Brault et at., 2007) or using virtual labs (Domingues et al, 2010; Domínguez et al., 2018; Naukkarinen and Sainio, 2018). Most of these approaches look for reinforcing conceptual skills included in the core knowledge of engineering or even integrating methods and technologies to develop the ability to transform knowledge previously acquired (Brault et at., 2007), rather than adding transferable skills, values, and sustainability attributes to contemporary engineering graduates. However, in reinforcing core engineering technical competences, all these activities promote work in groups of students and thus they boost some soft skills, mainly communication and teamwork that are needed as professional skills. This has been the main focus of the literature going back a long time (Taylor 1985) and still continues to the present (Sadikina et al, 2020), supported by the idea that engineers have to decide for themselves which is the best of many possible solutions to a problem that is often times ill-structured, or provided as loosely formulated problems. A common result in all the studies involving open-ended problems or activities is that there is enhanced opportunity for learning of a type which cannot be achieved using closed, well-defined problems. Therefore, although some soft skills are indirectly acquired, most of open-ended activities try to bridge the gap between problems with uniquely defined solution sets and the ability to solve fully real (open-ended) problems by considering real-life situations (Chen et al., 2016). Finally, in many cases, open-ended freeform surveys or reflections are employed to examine the outcomes of various PBL or CL approaches to help evaluate the rigor, teamwork, and scaffolding aspects of the assignment (Sammalisto et al., 2015; Witt et al., 2019; Sadikina et al, 2020).

In the described context, the aims of this paper are as follows:

1) To highlight the need for engineering graduate attributes which go well beyond necessary core knowledge, and incorporate transferable skills and values, traversed by sustainability attributes, to enhance employability and societal value within a world increasingly characterised by interconnected complexity and uncertainty, and a looming sustainability crisis.
2) To highlight and promote the key role that the application of open-ended activities and problems can play in providing such an engineering education.

Section 2 focuses on the first objective. Section 3 focuses on the second objective and presents examples of open-ended activities and problems from the two chemical engineering departments where the authors teach.

2. Graduate attributes for employers' and societal needs

We hold that contemporary chemical engineering graduates must acquire the requisite disciplinary knowledge, transferable skills, professional values and sustainability attributes for a successful career and valuable contribution to both the organisations in which they work and society as a whole. This facilitates a sort of virtuous circle, as illustrated in **Figure 1**, resulting in a professional engineering cohort and profession which is both more relevant to its society and employers, while also demonstrating enhanced attractiveness to potential recruits.

The graduate attributes of the contemporary engineer are schematically presented in **Figure 2**. At its core is the engineering graduate who must possess a core competence in (e.g. chemical) engineering knowledge and its application. This has always been a key remit of all engineering disciplines and will always remain so. These competences alone are far from sufficient however, as discussed below, including with respect to graduate requirements by professional bodies.

The four domains presented in **Figure 2** are also requirements of both employers and professional bodies to an increasing extent. These attributes can (and do) thus feed into both employer's requirements as well as wider societal needs (**Figure 1**). Employers require graduates with requisite technical expertise and depth of knowledge, but also ones capable of engaging in teamwork, employing excellent communication skills (with both technical and non-technical audiences) and capable of handling increased levels of uncertainty and complexity.

Society requires engineers who solve engineering problems, but in a way which do so safely, cleanly, without environmental degradation, and in society's best broadest interests (often achieved by recursive dialogue). The aforementioned graduate attributes and values, properly activated and employed, can thus hit both bases; employers can benefit and gain from meeting societal imperatives (by reputation and product sales), while society benefits from its interests being served, as well as by the quality and quantity of employers' jobs.

In the contemporary workplace however, employers desire graduates that are also well equipped with a variety of transferable skills and professional values, as outlined in **Tables 1 and 2** (informed by Lozano et al., 2017). Furthermore, for business, employers and young people, sustainability is becoming increasingly important. Some of the important cross-cutting sustainability attributes (considered under knowledge, skills, and values) are presented in **Table 3**. In **Figure 2**, the outer layer of 'sustainability attributes' both compliment and transcend each of the other three spheres as articulated in **Table 3**.

Many of the sustainability attributes proposed by Lozano et al. (2017) are included in **Table 3**, which represents a particularly important skillset of a sustainability-informed engineer. Furthermore, overall model presented in **Tables 1** to **3** offers a useful potential template for benchmarking programmes, and their respective courses or modules for the development of key graduate attributes.

Programmes have traditionally found it a greater challenge to incorporate appropriate transferable skills and values across their programmes, since these attributes have traditionally received much less attention (Wolff et al., 2018). A major challenge therefore is in how to include this material into already overcrowded three, four or five-year programmes.

This, we argue, requires an explicit reaching out and structural embedding of the respective domains within and across our programmes as well as through the traditionally well-covered domain of instrumental knowledge, all in an integrative fashion.

More particularly, a pedagogical approach based on creative open-ended activities and problem solving is a most effective means of developing each of the four domains. For the most part, this can be delivered through relevant and bespoke continuous assessment exercises, which are usefully employed both extensively and progressively throughout the programme. Currently, such an open-ended and integrative approach is perhaps often only extensively performed (if at all) towards the end of the degree programme in the guise of a capstone design project, and perhaps also by default through formal industry-based work placements, by which time it may be too little and perhaps too late to provide students with an appropriately developed skill-set sought by employers. In this light, the following section focuses on some exemplar applications of open-ended activities for the enhancement of technical competence, and development of transferable skills, professional values and sustainability attributes, and all under a broader sustainability context and ethos as espoused by Byrne and Fitzpatrick (2009).

3. Application of open-ended activities to develop technical competences, transferable skills, professional values and sustainability attributes

Open-ended activities are activities that students undertake that do not just have one unique answer. They often may have many different facets that students are required think about, such as technical, environmental, economic, ethical and social, and some of these may be in competition, resulting in trade-offs. Students may have to work individually and use their own initiative or work in groups and collaborate with others. These activities allow students to handle complex situations and open-ended problems for which there may be no unique solution, nor tidy problem specification or agreed framing.

3.1. Opportunities to perform open-ended problems and activities

Commonly used open-ended activities in engineering programmes applied to develop technical competences and transferable skills include the capstone design project, research project, and in some programmes, a work placement. These may also be used to develop sustainability attributes, for example in the design project. The capstone design project is a well-established and excellent vehicle for the practical application of programme threshold concepts in the context of an open-ended problem, and it thus represents a very useful and important exercise which connects many of the attributes developed throughout the programme. However, the application of engineering knowledge and skills in an open-ended context with high inherent uncertainty does not have to be restricted to the capstone design project or final year research projects, but it can be employed at various levels and scales right throughout the programme from first year.

Of course, this does not negate the need or value of closed system decontextualized problems, providing all the required data and where there is a unique solution, as typically find their way onto exam papers (under restricted time constraints), on short exercises and assignments. Such closed-ended problems are indeed useful, as starting points, to constrain the number of moving parts, and thus aid understanding, while providing a set of stabilisers to develop student confidence. The problem specification can then be increasingly opened, as students develop analytical and critical skills: first, giving extra data, then without giving some data, next problems with two or multiple solutions, and so on until those incorporating inherent uncertainty, including social, ethical, sustainability and environmental contexts.

Apart from open-ended design and innovation challenges, the requisite knowledge, skills and values can be developed in other ways too, such as through seminars, debates, in-class exercises and small design tasks, discussions with invited professionals, and so on. Moreover, while there is value and rationale in progressively developing more open-ended problem sets gradually throughout a programme, thereby developing students abilities to consider different solutions obtained by applying different criteria and framings (not only techno-economic ones), there is also a value to be had in immersing students in such problems, in an appropriate manner, right from the start of their programme, to demonstrate to them the messy contextualised world of real chemical engineering practice from the beginning.

Moreover, although design can be usefully used as a driver for upskilling and developing a confluence of graduate competences, as has been pointed out (Fletcher and Harrington 2018), it is not the only one. As mentioned above, the development of other types of bespoke open-ended problems requiring degrees of enquiry, innovation and creativity, may also help achieve these goals and additionally, and can readily be used from first year. Furthermore, many if not most practising engineers do not have to design, or participate in design, in their actual jobs but do engage in other engineering activities such as operation, maintenance, and troubleshooting, all areas which can be useful for devising open-ended problems which can help develop a range of competences, though these aspects are not as comprehensively taught as design is.

The following sections provide approaches and examples of open-ended activities and problems from the Chemical Engineering Departments at University College Cork and the University of Seville. These are presented to show how sustainability attributes, transferable skills, professional values and core chemical engineering technical competences can all be developed and enhanced through open-ended activities and problem solving. Given that each of the examples are of relatively recent vintage, formal graduate feedback or evaluation has not been undertaken, in particular in relation to the subsequent value of these exercises to graduates in the workplace (and compared with their predecessors). Some of the exercises have incorporated bespoke module questionnaires or student surveys however, and these are reported in the next subsections.

Moreover, from many informal conversations between respective lecturers and their students and graduates who have been engaged in these activities, they typically feel that by participating in such open-ended activities, they develop numerous soft skills, such as the ability:

- to productively engage in teamwork,
- to participate actively in a discussion, and across broader contexts, thus handling arguments beyond those purely in the scientific-technical domain,
- to make better presentations, and
- to get insight into and reflect upon different and competing facets that need to be considered when solving complex problems with more than one possible solution, making decisions as they will have to as future professional engineers.

3.2. Open-ended activities at University College Cork

Six open-ended assignments are presented, which seek to develop sustainability attributes and transferable skills. The first assignment is part of a first-year module, taken by all engineering students. The other five are part of two modules in 'Sustainability and Environmental Protection', which are taken in third year and final year by chemical engineering students. All are taught by one or other of the UCC authors.

3.2.1. Wicked problem assignment

Wicked problems are defined as complex problems without well-defined deterministic 'solutions' and even whose framings (problem description) are contested. A group assignment developed as part of an ethics module for professional engineers requires students to select a societal 'wicked problem' with an engineering dimension to research and reflect on, and ultimately present a report and presentation where various framings of the problem are outlined as well as possible interventions for each of these framings. This assignment is taken by first year students from across all engineering disciplines, and it is part of a module aimed at developing students' conceptions of complexity, uncertainty, risk, context and ethics as a foundational basis for productively engaging with sustainability. It is described in detail in an award-winning paper by Byrne and Mullally (2014). Some student comments are presented here which help highlight how the assignment seeks to develop macro-ethical (i.e. broader ethical issues at the societal and professional body level, such as around sustainability, and as opposed to those ones at the micro / individual / organisational level) awareness and a broader professional self-perception of formative engineers:

> *'Overall, I think by studying this wicked problem I got to explore and develop my learning regarding the social and ethical responsibilities of engineers. I have learned most engineering problems are wicked problems and so often don't have a clear solution.' / 'The module has proven to me that to be an engineer, being ethical is an essential tool to coming to a solution for a project or proposing a new idea. To be a good engineer, you must think of who you are affecting, what moral issues may arise and what sacrifices must be made to achieve your goal.' / 'At the start of term, I mistakenly assumed engineering to be a value free endeavour. My original thinking was that an engineer was paid to complete a task and their sole objective was to finish the objective to the specifications required ... [however] The engineer does indeed have an obligation to consider society and the environment in their decisions.'*

3.2.2. Book review assignment

As part of one of the sustainability and environmental protection modules, students are required to read and review a book of choice from a list including, for example:

- 'Sustainability by design' (Ehrenfeld, 2008) and 'The right way to flourish; reconnecting to the real world'' (Ehrenfeld, 2019) by engineer and industrial ecologist John Ehrenfeld.
- 'The myth of progress: toward a sustainable future' (Wessels, 2013) by biologist Tom Wessels.
- 'Enough is enough – building a sustainable economy in a world of finite resources" (Dietz and O'Neill, 2013) by Rob Dietz and Dan O'Neill.
- Confessions of a radical industrialist: profits, people, purpose: doing business by respecting the earth (Anderson, 2009), by industrialist and engineer Ray Anderson.

These books provide students with a provocative take on sustainability which challenges 'business as usual' approaches, requiring them to reflect and respond to the book's content while students are required to reflect on whether the book(/s) changed their understanding of the world/worldview in any way and on whether or how it may influence their future professional practice. The exercise can thus serve to enhance their critical thinking skills, their meta-thinking skills (students reflecting on their own thinking), and their ability to take on different (various disciplinary based) perspectives. It develops these transferable skills while feeding into a constructivist conception of learning, by offering the possibility of re-envisaging the world around them. As the review requires students to reflect on how it may or may not have changed their own perspectives, and how it may therefore impact on their own professional or personal actions, it has proven a useful and popular way for engineering students to engage with broader elements of their role and work. The assignment has been described by various students as being in turn ‘informative’, ‘eye opening’ (‘to the massive issues facing our generation’) and reflective: ‘the book review was useful … to force reflection’, while it ‘gave students the chance to interpret sustainability their own way’, was ‘good for broadening horizons’ and ‘encouraged us to take time to think about issues which we may not often think about’.

3.2.3. Life Cycle Assessment (LCA) assignment

This assignment emanates from a key perspective that permeates the Sustainability and Environmental Protection module, that is, a life cycle perspective. Essentially, the message is that it is not just the perspective of a single processing plant that counts, but rather the environmental impact/(un)sustainability of the whole life cycle of a product (or service). Allied to the assignment, a series of lectures is first provided on LCA and on product carbon footprinting. The assignment itself is an individual assignment where students perform an LCA on a generic life cycle of the production of a product that includes the possibility for end-of-life product recycle. The students are provided with raw life cycle inventory data, which is different for each student. They calculate the life cycle inventory and life cycle impact assessment in terms of the functional unit. This is first performed for the scenario of no recycle and then for partial and full recycle. 60% of the grade is awarded for the more mechanistic aspects of setting up and performing the calculations and results presentation, most of which is implemented in a spreadsheet. The final 40% is devoted to the interpretation step of the LCA. This is inherently a much more open-ended activity where recycling can have positive and negative impacts along the life-cycle, which can give rise to trade-offs, which students must consider. Also, students are encouraged to propose ideas that could reduce environmental impact hotspots. The students must make recommendations whether recycling should be considered or not and justify their recommendations. For the interpretation section, there is a wide variation in student performance. When the assignment grades are returned, the students are presented with the main aspects where performance was poor, which is mainly in the interpretation section.

Beyond the skills associated with constructing an LCA (as well as the associated difficulties and caveats), this assignment helps the students appreciate the importance of life cycle thinking. It helps them deal with a situation where there may be trade-offs and not one correct answer, and where they have to make recommendations and justify them. It also helps improve their IT and communication skills in terms of using a spreadsheet and report writing.

3.2.4. Transdisciplinary sustainability assignment

The following quote (Byrne and Mullally, 2016) represents the motivation and starting point underpinning the development of a transdisciplinary sustainability assignment:

> *'One cannot reasonably hope to expect disciplinary practitioners, educated exclusively in hermitically sealed silos within a 'multiversity' setting, to spontaneously develop the required understandings, skills and competences to work productively together in tackling larger wicked problems at some unspecified later stage of their respective careers or lives if they are not exposed to each other during the formative years of disciplinary education.'*

The assignment brings together third year students of the chemical engineering module on sustainability and environmental protection with students on an analogous but separate third year module on 'Sociology of the environment', taken by sociology and government students. This novel arrangement also facilitates the bringing together of visiting students (taking each of the modules) on a transnational basis - including from Brazil, Denmark, Germany and USA. The task is for mixed groups (of chemical engineers, sociologists and government students) to frame, consider, research and present on some chosen aspect of sustainability.

The exercise has resulted in some inspiring and innovative insights while transcending disciplinary silos in an ethos of open transdisciplinary. For a more detailed description see Byrne and Mullally (2016). The following respective engineering student comments on the exercise help elaborate this point:

> *'working in a team with vastly different opinions is hugely valuable to our careers in the future'*

> *'a major learning point was taking on board alternative perspectives of problems, outside of engineering solutions.'*

> *a 'transdisciplinary approach was enlightening; [an] engineering solution isn't always the only option'*

> *'As an assignment I felt it was interesting to engage with a different discipline than engineering; something we did not have an opportunity to do for the first three years of the degree. The main benefit of this was the different viewpoints and experiences that the sociology students were able to bring to the conversation.'*

'helps give a deeper understanding by giving different perspectives and looking at topics from different points of view'

A key point here is that, while this type of open transdisciplinary work is rarely done across our institutions, since our programmes are largely set up in silo-ised fashion with structures which mitigate against such endeavours, a huge amount can be accomplished 'under the radar' and from the bottom up, but it does require a degree of 'disciplinary humility' (Tripp and Shortlidge, 2019), after Byrne et al., 2017)) and more importantly the development of personal trust and understanding among academics from disparate disciplines. Among the sustainability attributes developed by the students on this assignment include inter/transdisciplinary work, communication, empathy and change of perspective, critical thinking and analysis and justice, responsibility and ethics.

3.2.5. Environmental consultancy assignment

This is a group "role-play" assignment where each student group has to imagine themselves as employees of an environmental consultancy firm who are sent to provide consultancy to an organisation whose senior management representative is 'role-played' by the lecturer. The organisation could be a chemical processor or some other organisation such as a bank or a hotel, and some basic information is provided about the organisation. The senior management representative is somewhat environmentally conscious and has heard that an environmental management system (EMS) approach could help the organisation improve its environmental performance. He has heard of the environmental consultancy firm and has made some initial contacts. As a consequence, the student group has been sent as a team of environmental consultants by their firm to make a fifteen-minute presentation to the senior management representative of the organisation, followed by questions, answers and discussion.

The objectives of the group presentation are:

1. To explain to the senior management representative what an EMS is, and to enlighten him as to why he should seriously consider implementing an EMS in his organisation.
2. To outline the environmental performance issues for the organisation and to provide a rough outline of a plan of activities that could potentially improve environmental performance, while also including a business case for the plan.

The grading is based on both individual and group performance, and the quality of the slides presented. Overall, the quality of the group presentations, both in terms of the oral presentations and slides, have demonstrated very good engagement by students with the assignment.

The assignment helps students develop a greater understanding of aspects of environmental sustainability in the context of an organisation. This is achieved by demonstrating an understanding of what an EMS is and how its implementation may benefit an organisation, and by brainstorming ideas for activities that may help an organisation improve its environmental performance, while recognising both business opportunities and costs. The assignment has a strong transferable skills element to it, in terms of helping each student enhance their team working skills and communication skills both orally and through slides. The students gain an initial experience of working and thinking as an environmental consultant, officer or manager, which could influence them in their future careers. Although no formal student assessment of the activity has been undertaken, the quality of the presentations given by the student groups demonstrate their active engagement and learning.

3.2.6. Environmental/Sustainability debates

Student environmental/sustainability debates are held on topics of environmental/ sustainability interest that are somewhat controversial, such as the following:

- The world will face major food and water crisis that will reduce the global population by billions.
- Wind energy is the way forward for generating electrical energy in Ireland.
- Human impact on biodiversity should be of major concern to humanity.
- Carbon capture, storage and utilisation will be a very important approach in the fight against climate change.

The students are divided up into teams where one team prepares and debates the pros side of the topic and the other the cons. The students are encouraged to investigate the topic from a broad perspective, which includes any economic, ethical and social issues in addition to environmental and technical. The first phase of the assignment requires students to research the topic and then each student must post a comment to an on-line discussion forum. Then, the students consider the comments posted on their debate and then each student posts a second comment, which may be a rebuttal to comments made by the other team. This process helps build up information on both sides of the debate. This acts as the basis for the debate itself, whereby each group must summarise their side of the debate and give a five-minute oral presentation during a regular class session. For each debate, there is five minutes for the pros, followed by five minutes for the cons, followed by five minutes of questions and discussion. Each group must then submit a final group written report, which has the following three parts: 1) summary of their side of the debate, 2) summary of the opposition's side, and 3) their final balanced opinion on the topic of the debate, considering both the pros and cons. Overall, student engagement with the assignment is very good, as evidence by the quality of the presentations and the vigorous debating.

The assignment helps the students develop their ability to present, argue and discuss issues of relevance to environmental protection and sustainability. Over the years, it became apparent that students tended to favour their own side of the debate and struggled to form a balanced opinion. Consequently, the students are strongly encouraged to understand and appreciate the arguments made by the opposition and that trying to form a balanced opinion is very important is this assignment. This highlights that many environmental and sustainability issues are complex and multifaceted and that they need to be open to and appreciate the complexity and multifaceted nature of these issues, and thus develops tolerance for ambiguity, critical thinking and analysis, empathy and change of perspective as well as communication.

3.3.Open-ended activities at the University of Seville

A number of open-ended problems have been carried out in some courses of the chemical engineering programme at the University of Seville. The focus here is initially on enhancing the development of core technical competences by looking at a closed problem and seeing how this can be transformed into an open-ended problem, followed by the inclusion of different aspects to the problem, which provide additional layers of complexity and uncertainty to the problem. The full extent of this problem can thus be addressed progressively throughout the degree programme, as the students' progress through different modules involving both core chemical engineering technical competences and those from other engineering disciplines. They thus also add safety, economics, environmental protection and sustainability to the technical competences, and they usually will have to make a decision by considering some criteria trying to reach a trade-off among the different options. The open-ended nature of the problem facilitates the development of transferable skills, such as information gathering, brainstorming, team-working and communication skills.

3.3.1. Converting the closed problem into an open-ended problem (from first year)

A classic closed academic problem, involving mass balances and general chemistry, is presented to first year chemical engineering students. The solution is unique, and the students have all the data they need to solve the problem, so it acts as a reference to open-ended activities in subsequent years. An example of such a problem is calculations performed on an industrial coal-fired boiler with flue gas treatment, as part of an electric power generation plant.

The first way in which the original problem is converted into an open-ended activity by omitting some data for a number of students. In this way, students must think about when they need to use these data, how they might find them and if required, and what assumptions they should make. For the rest of the students, the problem is presented with an excess of data, so not all are required, as oftentimes occurs in the real world, so that students learn to identify and use the necessary data, disregarding the rest.

This is implemented in the same subject for two groups of students and its extension in the second year, by simply changing some initial data to avoid the use of previous exercises given in first year. Normally, students find it confusing when dealing with more data than needed, and they become worried when there is a lack of data. Initially, they are a bit exasperated, but ultimately, they engage more strongly.

3.3.2. Extending the open-ended problem to include other chemical engineering subjects

Once we have the initial open-ended problem, more subjects/content may be added. For example, a fluid-mechanics open-ended problem is included, supported in a third-year subject entitled ‘Solids and Fluids Operations’. In this example, students have to compute the pressure drop of flue gases by deciding on the superficial velocity of gas in pipes. To solve the fluid-mechanics problem, students need to look for some other data and also make some assumptions, which must then be justified and revised after finalising the problem, just as it would be if carried out in the real world. Then, to boost the flue-gas from the boiler to the chimney, several fans are added with the added constraint of keeping a neutral pressure within an electrostatic precipitator (ESP) located in the flue-gas stream. There are several ways of doing this in practice.

The addition of the humidifier is also performed, which incorporates the mass transfer operation of humidification included in a third-year subject. The purpose of this equipment in which liquid water is injected finely pulverized, is twofold: to cool down the gas and to remove part of the ashes present in the flue gas. This new process unit adds a new open-ended activity regarding the design of such equipment from the feed data and specifications demanded at the outlet, partially decided by students, thus revisiting the original problem to move it forward towards an increasingly complex but real industrial plant. In fact, in this activity, the required temperature at the outlet of humidifier unit is important to ensure that the plume of flue gas emitted to the atmosphere does not fall to ground level. This involves finding out the temperature required in the chimney outlet, which in turns implies searching for such information and making more assumptions.

Next, control process and instrumentation is added to the problem, as there are a number of variables to be controlled (pressure in the ESP, among others) which involve the measurement of these variables and others, especially large disturbances. These may require the application of techniques of advanced regulatory control such as feed-forward action or a cascade strategy, which are very often used in industry. The students must select the sensors and transmitters from some constraints given in the problem, but they will have to make a decision among a myriad of possibilities by identifying and following various different criteria.

3.3.3. Involving technical aspects from other disciplines in the open-ended problem

The inclusion of knowledge from other engineering disciplines is implemented in a third-year subject termed 'Experimentation in Chemical Engineering'. Here, students work in teams of three members and, apart from working in the laboratory, they must carry out a short project on a small complete plant, with structural and electrical parts, throughout the second semester of the third year, which they must present to their classmates. In this way, mechanical aspects such as aspects such as the material selection (not only regarding corrosion but also from a mechanical point of view, which also involves the use of Standards), basic foundation of a particular unit or structure for some units and supports of pipes. Likewise, some electrical aspects are also added, such as the specification of electrical motors of some machines as, e.g., the fans and pumps previously designed. But some others such as basic elements on the electrical board.

Although it has not been carried out, the engagement of students of other disciplines, such as mechanical engineering or electrical engineering in these open-ended activities would be very useful since it would promote interdisciplinarity as a transferable skill to acquire.

The initial open-ended problem has become more and more complex, involving uncertainty and a number of potential solutions, involving team working, where a few solutions may be preselected during brainstorming sessions. Then, these are presented to the rest of their classmates, promoting in turn a wider discussion on the topic(s). In this way, the students enhance the following transferable skills:

- knowledge acquisition,
- dealing with uncertainty and complexity, and being aware that there is not one solution,
- team-work, collaboration and brainstorming,
- communication skills.

In the next two sections, more transferable skills and sustainability attributes are included.

3.3.4. Adding economics and environmental assessment

New criteria to make a decision on the best solution are introduced based on an economic assessment, accounting for investment, operating and maintenance costs. From these costs along with the revenues, taxes, potential borrowed money and its loan amortization, the minimum selling price of a specific product may be calculated with an internal rate of return over the lifetime of the installation. At this point, investment and operating costs regarding the environmental protection must be considered in order to transit towards sustainability. Students check on the performance of a current business, which may have a lower production cost than another one that is newer and more sustainable. From an economic standpoint, the selection of the current business might be direct, and one could think that sustainability is good but expensive. However, there are other facets to consider regarding this alternative way of thinking based on sustainability, so the traditional and current business could have a short life if some commonly used resources are scarce or involve a way to obtain them that leads to a severe and irreversible deterioration of nature resulting in the depletion of those resources and, hence, in closing the business. In this situation, and taking a long term to develop the business, the sustainable option could be the best option and, in fact, a more profitable option if the business could be extended over time. This is a clear example of competing facets and trade-offs in the open-ended activity assignments. In fact, a trade-off is a common situation in real life, and open-ended (real) problems and activities give the students the opportunity of thinking about advantages and disadvantages of using one or another solution and the responsibility of making decisions.

In this way, a further study directly related to the environmental assessment part of sustainability is Life Cycle Assessment (LCA) of the installation. Thus, students are promoted to look for alternatives to this installation keeping the same production objective (electrical power), which takes us to the next final part of this activity.

3.3.5. Integrating societal, ethics and sustainability contexts

The use of energy is a societal need that must be satisfied but not at any expense, i.e., the way to do this societal good must be developed within an ethical framework that includes sustainability, health and safety, as well as environmental protection. At this point, the students must consider other options to replace pulverized coal power stations, and this leads them to possibilities that may be totally different depending on a number of factors, which may be more or less limited by the teacher to avoid an excessive number of possible solutions. Thus, a boiler burning biomass has been suggested and, hence, a techno-economic assessment and LCA have been also performed to compare the new option(/s) with the original installation. Students will understand the problematic issues and challenges from a sustainability perspective, and they must look for solutions in the framework of this perspective.

4. Conclusions

In this paper, we argue that contemporary engineering graduates require disciplinary knowledge, transferable skills, explicitly developed appropriate professional values and sustainability attributes for a successful career, and make a valuable contribution to both their enterprises and society. To better achieve such attributes, we outline how open-ended activities and problems can provide a suitable platform to do this. In this way, students are guided to become autonomous learners, capable of productively engaging with their companies and with society.

In addition, open-ended problems allow for a suitable integration of the material from various branches of engineering, and beyond engineering, but the concepts should be taught and used from a practical and pragmatic point of view. In this way, the principal technical concepts (threshold concepts) of the (chemical) engineering curriculum can be continuously highlighted and integratively developed. Moreover, bespoke open-ended problems can be designed and applied to promote the development of relevant key graduate attributes, including interpersonal relations, systems thinking, anticipatory and critical thinking, interdisciplinary work, empathy and change of perspective, and communications.

The current paper, drawing from the experiences of two European universities that may be complementary and from which the authors have learned from each other, has aimed to operationalise how a fit-for-purpose contemporary programme that can develop key knowledge, competences and values. What is more, in doing so, it seeks to demonstrate in addition, how such graduates can help meet employability requirements and societal imperatives. Open-ended activities and problems, in their many guises, represent a useful vehicle in this aspect as they require creativity, communication and leadership, as students working on them can express their insights and arguments to their classmates and lecturers, thus integrating knowledge and developing transferable skills, professional values and sustainability attributes. Through a framework of open-ended activities and problems, students can thereby readily communicate, critically analyse, work in teams, work within and across disciplinary bounds, and handle uncertainty, in an increasingly post-normal environment. Problem specifications can also be opened increasingly and progressively, to help students develop the skills to handle problems with multiple framings and multiple potential solutions or interventions. The result is the development of a set of contemporary graduate attributes necessary now and in the future in the wake of inherent uncertainty, and amid pressing social, ethical, sustainability and environmental contexts.

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FIGURES AND TABLES

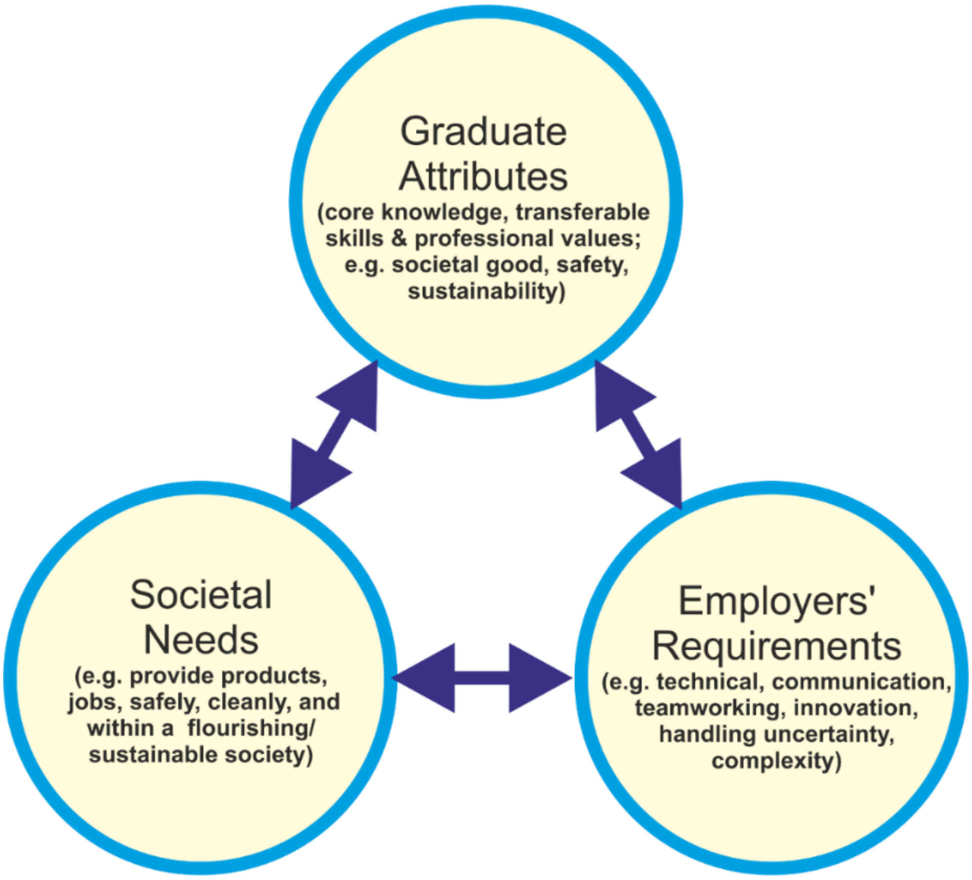

Figure 1. Coherence between graduate attributes and employers' and societal needs.

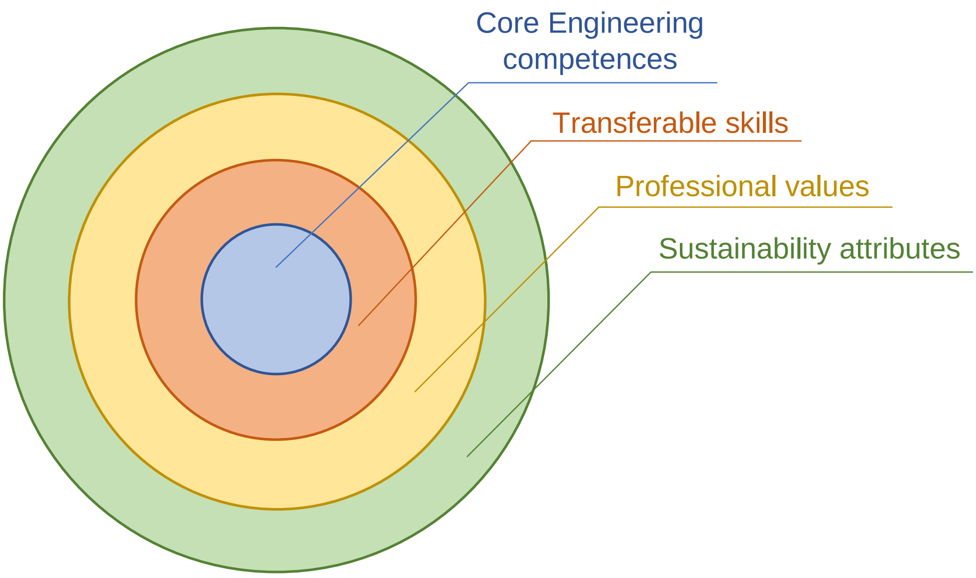

Figure 2. Graduate attributes of a contemporary engineer: Core Engineering competences enabled by professional values, transferable skills and sustainability attributes to satisfy societal needs and employer's requirements within a sustainability paradigm.

Table 1. Desirable transferable skills of a contemporary engineer.

Communication	Systems thinking
Dealing with complexity / uncertainty	Life-long learning
Inter and transdisciplinary	Problem solving / innovation / creativity
Entrepreneurial	Research skills
Information technology	Team working
Knowledge acquisition	Time management

Table 2. Desirable professional values of a contemporary engineer.

Personal integrity towards colleagues, clients, employers, employees and society A sustainability informed ethic, embracing social, environmental and ecological integrity, and equity A safety (including process safety) informed ethic An ethic of service to community and society	A professional ethic, including ongoing development and maintenance of technical competences and professional conduct and standards Embracing interpersonal relations and collaborative approaches to solving problems Seeking and empathizing with other perspectives, including developing transcultural and transdisciplinary understandings

Table 3. Sustainability attributes of a contemporary engineer.

– **Sustainability (core) knowledge** and **understanding**, including around the issues and challenges, as well as a deep appreciation of the importance of the social, ethical, ecological and economic dimensions of sustainability, and the interconnectedness of each. – **Sustainability skills:** ability to develop appropriate greener technologies, processes and approaches. – **Sustainability values:** e.g. concern for the environment, commitment to sustainable development, empathy, equality, diversity, commitment to social justice, flourishing communities, human well-being, etc.