More complex from the outset: theory, practice, laptops and natural foundations in a new 1st year chemical engineering course

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Abstract

A number of chemical engineering undergraduate programs the world over have reformed their curricula over the past decade, partly to incorporate more explicitly the challenges of 'sustainability'. This difficult process of curriculum reform benefits from alliances, thus addressing a range of inter-related concerns. In our case, the coalescing reasons were the quality of student learning, the transition from school to university in the light of societal transformation, and relevance to the profession's priorities, including sustainable development. After 5 years of preparation, our new 1st year course, trialling many elements of our new curriculum, is running in 2013.

We have borrowed from the forerunners in this endeavour a slightly reduced theoretical core, intertwined with an accompanying practice strand running throughout the four years of the program. At the entrance level this practice strand infuses the messiness of team dynamics and communication, health and safety concerns and environmental evaluation into the previously pristine space in which 'fundamentals' were to be learned for later referral. As part of the practice strand, expressing conceptually demanding material in writing has been added to the quantitative skills. In addition, to address differential preparedness, the curriculum is designed for cohort progression with 3-week re-work opportunities in winter and summer holidays. Additionally, all students are required to own a laptop but with support from university resources for needy students.

Most radically, our new first year course incorporates a 'natural foundations' strand that introduces nature not just as source of raw materials or as imposing limits on engineering prowess, but also as 'mentor and model'. This is inspired, in part, by our earlier work that sought to understand sustainable development as a threshold concept when introduced to our students only after they had cleared the "chemical engineering sciences". We present some examples of our interpretations of relevant sustainable development problems and text. On completion of the 1st semester of this year-course our aspiring chemical engineers have generally made good progress on "fundamentals", whilst both they and the teaching staff have been challenged by the deliberate critical placement of the theory in a broader environmental and social context.

1 Introduction

At about the same time as many other institutions in global society, in the early 2000s, the chemical engineering profession started to respond to the unsustainability of socio-economic development patterns, e.g. through the Melbourne Communiqué (IChemE, 2003), prominent papers in Chemical Engineering Science (Batterham, 2006, Clift, 2006) and the IChemE *Roadmap for 21st century engineering* (IChemE, 2007).

Chemical engineering has historically played a very limited role in African economies and their development, with exceptions in the oil-producing and refining nations and in the industrial complexes of Apartheid South Africa. Its close cousin (and sometime identical twin) process engineering has had a somewhat broader appeal and has recently been witnessing strong demand in many African countries on the back of resource-based economic growth, esp. in agro-processing and in minerals beneficiation. In regard to the booming African mining industry, it is worth noting that environmental impacts and the socio-economic development contributions of mining and metals production have received significant attention also from the early 2000s onwards (e.g. IIED, 2001).

Akin to many other engineering programmes, and partly in response to accreditation criteria of our outcomes-based degree, we (the Chemical Engineering programme at the University of Cape Town) introduced sustainable development considerations at that time into one core course. In our case, this happened when we re-worked the 4th year 'engineering economics' course into a 'business, society and environment' course in 2002 (as described and justified by von Blottnitz, 2006, and presented at EESD 2004 in Barcelona).

For a number of reasons, including but not centrally driven by 'sustainable development' concerns, we have been working on an entirely new curriculum since 2008, launching its new 1st year course in 2013. In this paper, we describe the rationale for this new curriculum, its main features, the new 1st year course, as well as some preliminary observations on having completed its first semester –focusing on sustainable development. This paper forms part of an emerging series of papers by the academic team leading the re-curriculation and does, in part, reproduce necessary contextual and factual information from other writings by the authors.

2 Context, basis and evidence for re-curriculation

The chemical engineering programme at UCT started in the 1950s and has had periodic changes made to it, the last major one in 1995 with the establishment of a first year engineering course and the inclusion of design courses in second year. The programme takes in approximately 130 new students each year, with a wide demographic spread comprising a majority of black South African students. The most recent complete throughput analyses show that approximately two thirds of the intake graduate in the programme, and only half of these graduates complete in regulation time.

The Department has been conducting education research on student learning in its undergraduate programme over nearly two decades (Case, 2012). Together with other evidence, shortcomings of the current curriculum have been argued to be (Case et al., 2013):

a) Limited structures and dated approaches to support the school-university transition
b) Overload which militates against high quality learning in the programme;
c) A lack of coherence and integration in key areas across the programme, most notably in mathematics, computing, teamwork and communication;
d) Inadequate exposure to the chemical engineering profession, also "somewhat out of touch with the ways in which the profession is changing, in particular a significantly increased emphasis on sustainable development";
e) No opportunities for specialisation and limited choice of electives.

For the purposes of the present paper, it is worthwhile to elaborate on point d) – the astute reader will have noted that to make the case for the long and resource-intensive journey of re-curriculation, an alliance is needed and also, that in our case, this alliance was led from an educational perspective. Readers familiar with what may be termed the 'cleaner production technology retrofit problem' would, however, also know that ‘green’ can often not be implemented on its own merits, and must be astute to the opportunities that arise during ‘new plant design and installation’. Beyond this good reason for allying however, we were also in a position to draw on research on what sustainable development conceptions our graduates hold. This work investigated ‘sustainable development’ as a possible ‘threshold concept’, which to learn properly involves some discomfort of parting with familiar worldviews. The findings point to the need to allow students more time to ‘navigate the liminal space’ – a time of uncertainty in which the implications of the new worldview are explored, of the limitations of the old way of seeing things, of experimenting and of changing one’s identity (Sibanda et al., 2011).

Building on these perspectives and informed by the latest international scholarship on engineering education, the new curriculum is centred on the following two interrelated objectives:

1. Improve the quality of student learning in the programme in order to increase the throughput of successful graduates, as well as the quality of those graduates.

2. Increase relevance of the curriculum to contemporary and future foci in chemical engineering (including research-led teaching and sustainable development).

3 Intended and implemented reforms

In designing a new curriculum we have been guided by international developments at top chemical engineering institutions, most notably University of Sydney, University of Queensland, and Imperial College. The new programme will remain a four year bachelor’s programme, meeting the requirements of the Engineering Council of South Africa (ECSA). The core curriculum is sufficiently unchanged that thus will not need to register as a new programme. However, in structure and in modes of teaching and learning it is significantly different to the current curriculum.

3.1 The (intended) new curriculum

We considered both problem-based and project-based learning curriculum models and have made a deliberate choice (justified by Case, 2011) to design our curriculum as ‘project-centred’, where there is a strand of project work running throughout the curriculum but theory is still explicitly taught alongside project work.

The programme will involve a larger proportion of elective courses than previously, with the introduction of science electives and a refocusing on the humanities elective space, including a compulsory language course. Full year courses in each year of the programme are envisaged, allowing for better integration of material across topics, and the inclusion of a sustained strand of project work.

We are fully aware that graduates in the 21st century will need to be able to embrace complexity much more readily. We are therefore letting go of key guideline of our 1995 curriculum that attempted to build the ability to understand reasonably complex systems in a step-wise fashion as shown in Table 1, instead embracing the messiness of allowing a multi-level approach from the outset.

On the other hand, with the intention to improve the quality of conceptual understanding, we are structuring our new curriculum with a clear and logical progression of key ideas. Year courses will be structured into modules which will mean that within the course at a given time students will be focusing intensively on one knowledge area, rather than experiencing daily “45-minute drip-feeds of content” across a number of courses.

Table 1: Approach to complexity in our old and new curricula

1995 curriculum		2015 curriculum	
Unit (once-off)	Dominant approach to building ability to deal with complexity	**Unit (nested & recurring in modules)**	Dominant approach to building complexity
Year 1	Academic readiness, exposure to the discipline, identity-formation	**Theory**	Blocked, focused, to be mastered (80%)
Year 2	Chemical engineering science: multi-phase single-component, or single-phase multi-component	**Practice**	Stranded vertically, demonstrated, learnt by doing, competency must be shown (80%); systems modelling and simulation admitted much earlier
Year 3	Chemical engineering science: multi-phase, multi-component (unit operations)	**Project**	Application of (initially limited) theory, through a (limited) set of practices, open-ended, initially heavily scaffolded
Year 4	Systems of systems (flowsheets); process simulation; heuristics for their design; economic and environmental analysis thereof	**Integrated assessment**	Summative assessments that may draw from theory, practice and project spaces

3.2 The new 1st year course

The first year course which has been rolled out in 2013 contains the course design features that are envisaged for the second and third year core courses, and thus the evaluation of this trial course is an important stage in the overall curriculum reform process.

The course is structured into four six-week modules, each with the generic structure showed in Figure 1. Initially bewildering for students, it is actually derived from a set of simple rules, and first indications are that the repeated application of these simple rules is indeed allowing complex phenomena to take root in the learning space.

A number of features are evident in Figure 1. Firstly, this is a big course, occupying 4 morning lecture slots plus two full afternoons per week. The 'theory' space is coloured in blue and it can be noted that lecture sessions alternate with 'exercises' which can be considered to be mini-tutorials. The first two weeks of the module are heavy on theory and the project space (coloured in orange) commences at the end of this period. Termed 'practice' are the lecture plenary inputs which students need in order to tackle the project work. In the projects, students work in groups but tackle both individual and group tasks. Using tutors we have managed to get a fast turnaround on feedback on the project tasks such that students can use this feedback going forward in the project. Mastery tests are signalled in purple and it can be seen that retests are scheduled into the module structure. Some of these tests are conceptual mastery tests and others are skills competency tests.

Week 1

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Theory 1		Theory 3	Exercises 3	Theory 4
4 - Meridian	11:00-13:45					
6	14:00-14:45		Exercises 1			Exercises 4
7	15:00-15:45		Theory 2			Theory 5
8	16:00-16:45		Exercises 2			Exercises 5

Week 4

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Mastery Test		Theory 10	Exercises 10	Practice 6
4 - Meridian	11:00-13:45					
6	14:00-14:45		Practice 5			Practice 7
7	15:00-15:45		Project/Prac			Project/Prac
8	16:00-16:45		Project/Prac			Project/Prac

Week 2

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Mastery Test		Exercises 7	Theory 8	Exercises 8
4 - Meridian	11:00-13:45					
6	14:00-14:45		Theory 6			Practice 1
7	15:00-15:45		Exercises 6			Project/Prac
8	16:00-16:45		Theory 7			Project/Prac

Week 5

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Mastery Make-up		Theory 11	Exercises 11	Practice 9
4 - Meridian	11:00-13:45					
6	14:00-14:45		Practice 8			Class Test
7	15:00-15:45		Project/Prac			Class Test
8	16:00-16:45		Project/Prac			Class Test

Week 3

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Mastery Make-up		Theory 9	Exercises 9	Practice 3
4 - Meridian	11:00-13:45					
6	14:00-14:45		Practice 2			Practice 4
7	15:00-15:45		Project/Prac			Project/Prac
8	16:00-16:45		Project/Prac			Project/Prac

Week 6

Period	Day	Monday	Tuesday	Wednesday	Thursday	Friday
1 - 2	08:00-09:45					
3	10:00-10:45	Practice 10		Theory 12	Exercises 12	Practice 12
4 - Meridian	11:00-13:45					
6	14:00-14:45		Practice 11			Project
7	15:00-15:45		Project/Prac			Project
8	16:00-16:45		Project/Prac			Project

Figure 1: Generic module structure.

Adding further to novelty, the course is one of three at the University of Cape Town (UCT) piloting laptops for use in class (UCT has made a special allocation to assist Financial Aid students in this regard). The course is thus also trialling a range of innovative uses of computer technology to assist in teaching and learning, including more intensive use of the course website, a paper free course, the use of online software with 'clicker' type applications and project work in the class venue which uses computer applications for calculations, text production, presentation preparation and drawing.

Table 2: Sustainable Development Topics relative to the whole course

Content summary for CHE1005W					
Theory (12 per module; each with a tutorial)	**No**	***Practice (12 per module)***	**No**	***Project (15 per module)***	**No**
Process Design	5	Economic Analysis	3	Flowsheeting	8
Natural Foundations	13	Environmental Analysis	8	Environmental Analysis	8
Mass balances	21	Unit Conversion	4	Economic Analysis	4
Energy Balances	3	Social Impact	1	Maths in Context	11
Systems of units	2	Learning Community	2	Social Impact	4
Process Analysis	4	Modelling and Computing	11	Modelling and Computing	12
Total	48	Safety	2	Communication	13
		Identity Formation	10	Total	60
		Communication	5		
		Total	46		

Additionally, there is one practical per semester, for a total of 8 sessions.

3.3 The "Natural Foundations" theme

Within this course, the theoretical underpinning for sustainable development comes through a set of lectures and exercises around the theme of 'Natural Foundations'. It aims to build in students an adequate grasp of i) the source and nature of raw materials, ii) the limits and functioning of the planet's resources and iii) the possibility or learning from nature. This has involved more engagement with text and an inclusion of more open-ended debate into the course. This has to some extent raised the cognitive demand of the first year course, which historically was more located in relatively simple calculations. Sustainable development topics are also reflected in the choice of project assignments.

4 Interpretations of sustainable development

At the time of writing, the first semester of the new course has been completed, involving the 130 students, 8 tutors and 2 professors (the first two authors), each one of us leading one module (and thankfully being 'off teaching' in the other). We have experienced both very interesting and very challenging situations (and this is how some students have also described the course). Within the 6-week module, we have spent an estimated 25 hours per week on this course. Having taught the predecessor 1st year course, we had standard materials at hand for the classical 'Design and Analysis' components of the course for which we continue to use Duncan and Reimer's (1998) text – but we had to assemble the natural foundations theory as well as much of the related practice, project and integrated assessment materials. We were fortunate to be able to recruit a retired colleague (the third author) to assist with preparing materials. Whilst one of us is active in 'sustainable development' research, we are cognisant of the wide and often contested interpretation of this field, and therefore are making use of the platform of this conference to present some examples of our interpretations in the following sections, to elicit feedback. The examples are all in the context of water, which was deliberately chosen as context for the first two modules of the course, to reinforce one of the theoretical learning fundamentals, viz. confidence to work with volumes and concentrations. Energy will form the context for the second semester.

4.1 "Natural Foundations" theory

The four system conditions for sustainability (TNS, 2013) have been used to structure thinking about process engineering activities in production, consumption and decomposition in the industrial economy. Table 3 shows an example of each explored in the context of the hydrological cycle.

Table 3: Examples used to structure thinking about water and sustainability

Breach of sustainability condition	**Example (and mechanism of action)**
1. Systematic transfer of substance from the lithosphere	Transfer of ground-water borne arsenic into society (and the environment), Bangladesh; (poisoning, cancer)
2. Systematic release of non-degradable chemicals into the ecosphere	B. Nonylphenols in detergents (e.g. wool processing in South Africa); (Hormone disruption)
3. Systematic physical degradation	Aral sea; (overharvesting)
4. Systematic undermining of ability to secure livelihood	Land owner H_2O rights in Apartheid South Africa ; (inequitable access)

4.2 Practice: the ability to write about "sustainability"

Example: The 3rd afternoon in the project for module 1.

Today you are going to investigate the phosphorus cycle. You will need to establish the flows of phosphorus around this cycle and the time frames for these flows, as well as the impact humans have had on this cycle.

Member A: … the phosphorus cycle on land …

Member B: … the phosphorus cycle in rivers and lakes …

Member C: … the phosphorus cycle in the oceans …

… The written description (use full sentences) must be between 200 and 250 words long, and include the number of words in brackets after the last paragraph, on the right. …

4.3 Project – water reuse or desalination

Example: final session of the module 2 project.

In this session you will prepare for the final report on this project, which will take the form of an oral presentation by the whole group.

Southern Africa is generally short of water for urban usage, and it is anticipated that most urban centres will experience a shortfall in supply over the next twenty years. The focus of the final report is to examine the recycling of waste water in one of the large urban centres in South/Southern Africa.

What you will need to do, in the light of what you have already done in this project, is to find out the water situation in your chosen centre:

- Current and predicted usage over the next twenty years,
- Current and predicted water supply over the next twenty years,
- Possible use of water recycling to meet any predicted shortfall in supply, and
- Possible use of desalination (of seawater or brack water) to meet any predicted shortfall in supply.

4.4 Integrated assessment

Example: Question 2 (making up 1/3rd) of the June test.

You have been appointed to a position in the municipality of a small town in South Africa. Local environmental groups have reported a problem of eutrophication in a local dam which receives treated water from a wastewater treatment plant. There is also an informal settlement located alongside the dam which does not have formal sanitation and whose wastewater flows directly into the dam. [Some data then given.]

a. What is eutrophication? Explain briefly in your own words how it may kill aquatic life.

b. Represent the flows in the scenario above in the form of a block flow diagram. In your diagram, represent the total flow into the dam as a combined stream. Label all streams and all units.

c. Calculate the P concentration (in mg/l) as well as the total flow rate of the combined stream flowing into the dam.

d. Calculate, in days, how long it will take for the dam to become eutrophied.

e. Middle-class ratepayers say that the informal settlement causes the eutrophication of the dam. Respond and propose a course of action.

5 Conclusion

Building sufficient consensus among faculty for a curriculum overhaul has taken some time. Examples from other leading institutions have been helpful. It was useful for the 'sustainability' agenda to ally with an 'education' agenda, both to make the case, and to intertwine the goals of what is to be learnt with the quality of the learning outcomes. The rollout of a new first year course has been an important trialling exercise for the overall curriculum plan. With this course carrying the essential structure that is intended for the core chemical engineering courses in the second and third years, many important lessons are emerging.

Adding complexity to the initial, almost bewildering, experience of transitioning from school to university has been challenging. In school there is a clear set of notes or a textbook which describes exactly what you need to know – nothing more than this can be asked in the final school examination. Particularly with the inclusion of topics in natural foundations, the new first year course has opened things up considerably. This aspect of the course expects students to look critically at the outcomes of the modern resource-based economy. The inclusion of a project strand in the very first module provided an additional challenge but also further opportunities for engagement and stimulation. Repeating the same pattern of theory, practice and project in the second quarter has helped to allow complex learning processes to unfold with much less anxiety.

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