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INTRODUCTION TO CHEMICAL PRODUCT DESIGN
A Hands-on Approach

L. KAVANAGH* and P. LANT

Advanced Wastewater Management Centre (74-305), University of Queensland, St Lucia 4072, Australia

Chemical product design has been introduced into the Chemical Engineering curriculum at The University of Queensland through an introductory Second year subject followed by product-specific electives in third year (biochemistry, food technology, materials and particle and polymer science, physical chemistry and so on) and culminating in a capstone year-long project in the fourth and final year.

In keeping with problem-based learning strategies, experiential learning is gained in the Second year subject, which was first offered in 2003, by two hands-on reverse engineering assignments and a business skills subject. The fourth year course, which was inaugurated in 2004, involves the students in the design and promotion of actual cutting-edge products requiring initial market research and experimental product development.

Both Second and fourth year students taking the courses have been highly motivated and committed in their efforts to produce quality final deliverables. Student performance and lecturer reflections indicate that learning objectives have been achieved and interest stimulated. Reactions from students to this new and somewhat innovative stream of courses have been positive although it has been indicated that the work load is significantly higher than other subjects with the same credit rating. The courses will continue to be offered and will be strengthened through modifications arising as a result of lecturer and student feedback.

Keywords: chemical product design; experiential learning.

INTRODUCTION

Recent years have seen the growth of the 'chemical product' (Cussler and Wei, 2003) that can be described as having high-value, low-volume, and limited life. These products are always subject to continual improvement and hence are rarely required to be produced over a period greater than 2 years.

This represents a paradigm shift for chemical engineers who are more used to designing, optimizing and operating plants designed to produce commodity chemicals or, more critically, are taught to design, optimize and operate these processes. Chemical product design (CPD) therefore offers new challenges and opportunities (Cussler, 1999) for chemical engineering educators who wish to see their students equipped to make a significant contribution to industry and research organisations across the world.

Business skills are an integral component of successful CPD. The success of short-lived products requires market research, entrepreneurship and the ability to put together a business plan to raise venture capital—not the core domain of the chemical engineering educator.

**Correspondence to*: Dr L. Kavanagh, Advanced Wastewater Management Centre (74-305), University of Queensland, St Lucia 4072, Australia.
E-mail: lydiak@awmc.uq.edu.au

The Department of Chemical Engineering at the University of Queensland decided to update the curriculum by acknowledging the need for chemical engineers to embrace CPD. The objective of the stream of CPD courses was to keep CPD teaching real and experiential and thus allow students to maximize their learning. This dovetailed with the unique curriculum structure adopted by the department in 1999, wherein project-based core subjects are used to put into perspective and practice the theoretical concepts learned in other traditionally-taught subjects.

This paper details:

- the design of the CPD stream of courses;
- the teaching methods employed;
- lecturer and student reflections on the first year of teaching the courses.

THE CPD MINOR

Engineering is a 4-year full-time degree at The University of Queensland. Year 1 of study is a general year involving basic mathematics, chemistry, physics and engineering fundamentals. Students then specialise in Chemical Engineering in years 2–4. Each year students generally undertake eight semester-long subjects (i.e., four subjects a semester).

Table 1. CPD minor electives.

Year	Semester	Elective
1	1	Physics and engineering of materials
2	2	Introduction to CPD
3	2	Specialist product course (e.g., biotech, biomedical, nanoparticle, polymer, plastic or food technology)
4	1 & 2	CPD (the capstone course)

The engineering programme offers students a number of elective courses. A coherent set of electives comprises a minor; CPD is one such minor. Table 1 summarizes the CPD stream that comprises three single-semester electives and one full-year elective. The electives comprise approximately 16% of the total programme; the remainder of the programme delivers the traditional chemical engineering subjects including process design.

This paper discusses only those CPD-specific subjects offered in years 2 and 4. The year 3 specialist subjects offered both within and outside the chemical engineering department have not been examined in any detail with respect to the requirements of CPD. There have been difficulties with respect to timetabling and initial discussions with coordinators of appropriate subjects have shown that not all information is relevant and that there may be some overlap with the year 2 and 4 subjects.

INTRODUCTION TO CPD (YEAR 2)

Overview

Year 2 chemical engineering students have only rudimentary knowledge and skills with respect to the practical application of chemistry, physics and mathematics. Subjects such as mass and heat transfer, process control and reaction engineering that form the basis of chemical product design are undertaken in the third year of their studies. Due to this lack of fundamental chemical engineering knowledge, their introduction to CPD focuses on reverse engineering, whereby the students start with the finished product and take it apart to see 'what makes it tick', in order to maintain a hands-on approach.

Table 2 shows the learning goals and the teaching and assessment methods used to achieve the learning goals.

Generic Product Design

Figure 1 shows the sequence of key-note lectures given; where two lectures are specified for a particular topic, the first is generic and the second concentrates on chemical engineering. Each of the lectures is followed by a workshop designed to get the students to utilize the methodology presented in the lecture. Students are then required to capitalize on these lessons by completing the workshop at home and submitting their solutions for assessment.

As an example, one workshop, held after Lecture 4, requires the students to examine the specific needs associated with a household self-sufficient with regard to water usage. During the workshop, the students work in teams to brainstorm and rank needs for such a residence using an idea-generation toolkit and one of a number of ranking methods (Ulrich and Eppinger, 2004; Cussler and Moggridge, 2001; Dym and Little, 2000), all of which are presented in the preceding lecture. The individual student then compares these ideas against a benchmark and converts them into preliminary engineering specifications as the 'take-home' part of the workshop.

Chemical Engineering and Product Design

The two reverse engineering projects are designed to give the student an insight into chemical product design. Examples of previous projects are:

- 'Cracking the beer market' (adapted from Farrell *et al.*, 2002): students explore properties such as head formation/stability, pH and colour within the laboratory and relate this to the market with the aim of exploring the potential for a new beer product (Figure 2 shows one student's attempt at producing a beer market map that shows likely niches for a new beer product).
- 'Die swell': students operate and model polymer extrusion equipment in order to establish whether the die swell will be acceptable with respect to a proposed new polymer product.

Table 2. Second year learning goals.

Learning goal	Teaching method	Assessment	Weight (%)
Understand generic process of new product design	one-hour key-note lecture followed by 2-hour workshop	Individual workshop portfolio, requiring extra 1–2 hours work after each class-based workshop	20
Gain insight into mechanisms of CPD	Two reverse engineering laboratories	Two assignments based on reverse engineering laboratories	40
Develop business enterprise skills	Guest lectures Business skills programme	Trade display Business plan/annual report Business management/success[b]	40[a]

[a]The 40% mark attributed to the Business skills programme comprises a team mark for the performance/effectiveness of the company (20%), and an individual mark for contribution to the company's progress/success (20%). Individuals are peer assessed on the basis of degree of responsibility, team work, contribution to company success, performance in meetings, drive, initiative and effort.

[b]The team mark is based on a number of categories: profit, company success (administration, marketing, manufacturing, customer satisfaction, ability to overcome obstacles and teamwork/spirit), deliverables (business plan and annual report), knowledge/experience (understanding of nature, scope and demands of business, and grasp of requirements for establishing and operating a business) and communication (meeting effectiveness, delegation, organization and coordination, and reflection and articulation of experiences).

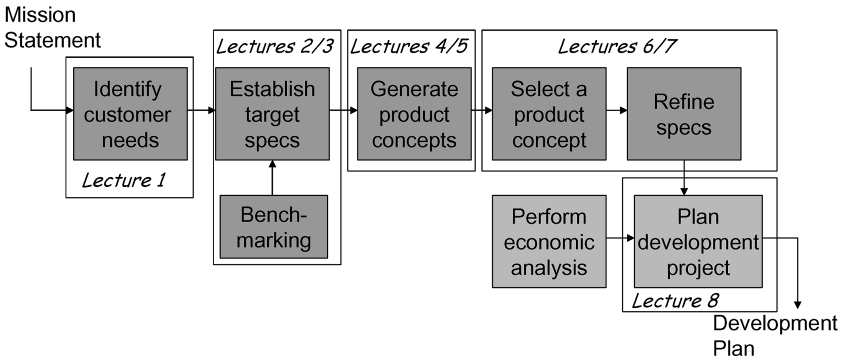

Figure 1. Preliminary product design (adapted from Dym and Little, 2000).

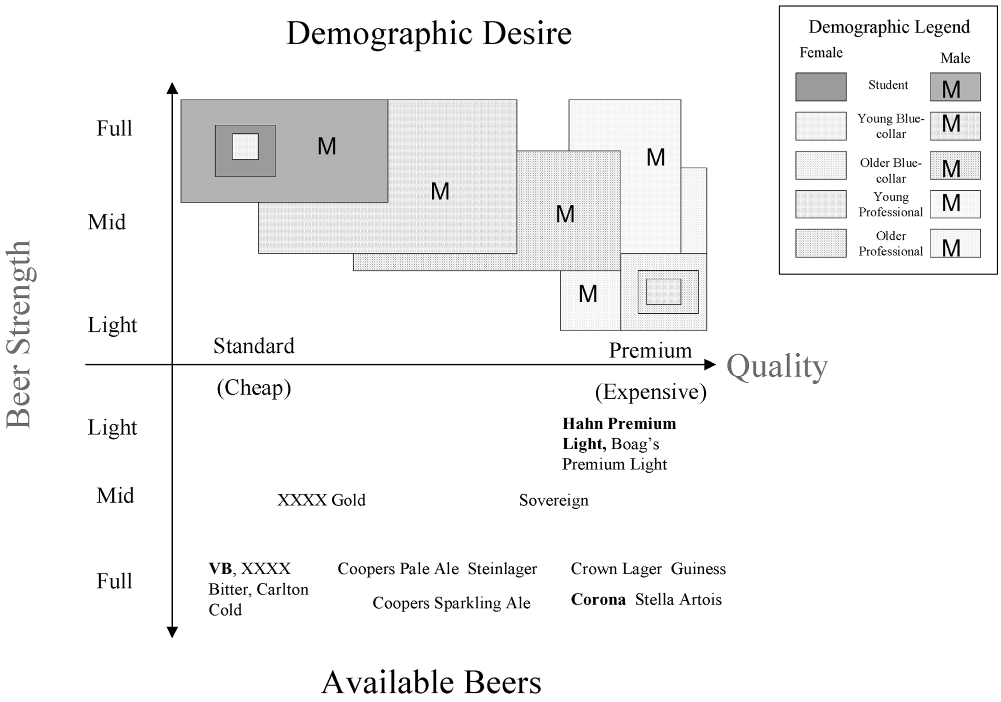

Figure 2. Beer market map (student work, 2003).

Business Skills

Business skills are taught to the students through the use of a Young Achievers Australia[1] module designed to develop business enterprise skills and capacities requiring a weekly 2-hour business/board meeting that incorporates a number of oral presentations by various company members. An experienced chemical engineer working in business operations for a large process company attends most of these meetings in the capacity of an industrial mentor. The programme is coordinated by the lecturer and undertaken by the students as a class team (approximately 14 students).

[1]Young Achievers Australian (YAA) is a not-for-profit organization that runs a cross-disciplinary programme 'to offer young people a practical, stimulating, satisfying, and successful introduction to business' (YAA, 2004). Each year over 400 YAA Business Skills programmes are operated across Australia, mostly within secondary schools over the period of a year, but also within tertiary institutions over the period of one semester.

The module, which runs for the entire semester, requires the students to:

- choose and register a company name;
- capitalize the company through the selling of shares;
- develop a product proposal and produce a business plan (written reports);
- elect executive directors for marketing, manufacturing, HR, finance and environmental divisions;
- produce and sell a product;
- undergo audits, training and improvement (company and manufacturing); and finally,
- liquidate, distribute dividends and pay taxes.

THE FINALE (YEAR 4)

The final capstone course, which is run over two semesters in year 4, involves students in the design and development of a cutting-edge chemical product. Teams of students are assigned an academic or industry mentor and work with the mentor on a real project for which they are required to sign confidentiality and Intellectual Property agreements.

The students are given some latitude in specifying the project deliverables and also the methods whereby they achieve the learning objectives. This is deliberate as mentors give only technical guidance and course lectures/workshops are necessarily generic and not specific to the wide range of projects offered to the students. Therefore, successful completion of the course requires students to design and undertake their own product development experiments and thus take charge of their own learning.

Teaching and assessment methods of the course are detailed in Table 3. They are designed to give equal weighting to business and technical skills.

In the first semester, the students researched product information on both technical and business fronts. The former included a literature review and familiarization with laboratory procedures and equipment, whilst the latter involved market research. This allowed the students to:

- follow the product design procedure outlined in Figure 1;
- draw up a plan and budget for product development that they would undertake in second semester.

The second semester saw the students heavily involved in the development of their selected product. To facilitate this, there were fewer lectures and workshops. These lectures focused on product marketing tools: trade displays, websites for e-commerce and business plans.

The chemical products developed in 2004 by 14 students working in teams of two or three are listed below.

- 'Low carbohydrate honey': students developed methods of extracting flavours from honey and extending these with gum to produce a low carbohydrate product that they planned to market locally (academic mentor).
- 'Chemical reaction/separation membrane scale-up': students developed a model for the scale up of molecular sieve silica membranes, researched likely applications and proposed a start-up company in conjunction with investment from a leading international player (academic mentor with industry backing).
- 'Transient heat transfer software': students developed a software model capable of predicting temperature gradients and heat transfer rates under transient operating conditions for one-dimensional multi-layer conduction calculations. The model was proposed to be sold via the internet and also to be used as an in-house consultancy tool (academic and industrial mentors).
- 'Titania air filters': students developed a method of securing a photo-catalyst to a stable medium, designed, constructed and operated a proto-type air filter, and planned to market the photo-catalytic air filtration system internationally (academic mentor).
- 'Nanomaterials for biomedical purposes': students researched the use of nanomaterials in biomedical devices, undertook laboratory tensile testing of promising materials that they developed, and planned to sell or licence their findings to large international biomedical manufacturers (academic mentor).
- 'Fruit leather': students developed both new formulations of fruit leather and manufacturing processes in an effort to exploit an adult market niche that their research exposed. Their start-up company proposed to sell the novel fruit leather to the domestic market initially (academic mentor with industry backing).

LECTURER/MENTOR REACTION

Reflections on the second and fourth year courses from an academic's point of view are that:

- there was a high degree of enthusiasm exhibited by the students taking the courses. Although many students complained of the large workload, no student decreased their input, indeed most were so highly involved in their project(s) that the requirement for successful product design appeared personal and not driven by final grades;
- the final deliverables were mostly high quality suggesting both student interest and achievement of learning goals;
- evidence was seen in the second semester of the fourth year course of students taking charge of their own learning as they began to take control of their projects, their time management and their experimental programme; and

Table 3. Year 4 learning goals.

Learning goal	Teaching method	Assessment	Weight (%)
Design and develop a chemical product from concept to manufacture	one-hour keynote lecture followed by 2-hour workshop	• Portfolio of completed workshops (both semesters) • Market research report (Semester 1) • Business plan (Semester 2)	16 15 15
Become familiar with the process of business planning and marketing	one-hour keynote lecture followed by 2-hour workshop Guest lectures	• Portfolio of completed workshops (both semesters)	As above
Develop engineering research skills	Mentor liaison Laboratory work	• Proposal for laboratory work (Semester 1/2) • Technical development report (Semester 2)	7 10
Gain in-depth knowledge about a particular type of chemical product	Mentor liaison	• Literature review (Semester 1)	7
Increase communication skills	Website production lecture/workshop Trade expo visit	• Seminars of findings (both semesters) • Trade display (Semester 2) • Website (Semester 2)	16 7 7

- the level of input into lectures and workshops and almost 100% attendance suggested that students had developed a genuine interest in CPD.

Discussions with the mentors involved in the fourth year course confirmed these reflections but also exposed a couple of problems:

- although some mentors managed to use the student findings to further their own research, there was a large demand on the mentor's time that was not always equitable with respect to positive research outcomes;
- laboratory facilities and associated budgets were not always available to the students with postgraduate research students having higher priority; and
- some laboratory procedures, such as those associated with membrane production, were not possible to master in the time available to the students. These students therefore were limited to modelling the process and using results obtained by PhD researchers.

STUDENT REACTIONS

Subject Questionnaire

The University of Queensland has an evaluation procedure consisting of a questionnaire distributed to students at the beginning of the final subject lecture. Students are asked to indicate their level of agreement with a number of statements and to write comments as applicable. Average scores from both the second and fourth year subjects are shown in Table 4. Scores are encouraging with the exception of that for workload that indicates that a great deal was asked of the student. However, some of this extra work was observed to be occasioned by the student's enthusiasm for the subject and their personal interest in the success of their projects.
Verbal and written communication with the students showed that there was a high degree of satisfaction with the courses and some went as far as to say that it was the most enjoyable course that they were currently doing. Written feedback on the questionnaire showed that the students liked the way the subject was presented but that they had indeed put in more hours than for any other subject.

Table 4. Subject evaluation [Scores: 1 (strongly disagree) to 5 (strongly agree), $N = 14$].

Question/statement	Second year (2003)	Fourth year (2004)
The course has fulfilled the stated objectives	3.9	3.6
The workload was appropriate for the credit point value	2.6	2.8
My critical abilities have increased during the course	4.0	3.6
I have developed interest in this course	3.9	3.8
I have developed a good understanding of the field	3.8	3.8
I have developed professional skills in this field	3.8	3.8
Overall, how would you rate this course?	3.8	3.6

Table 5. Second-semester scoring matrix (Year 4, 2004).

	Delivery				Deliverables					Other?	
Learning outcomes	Key-note lectures	Guest lectures	Workshops	Mentor meeting	Oral presentation	Technical report	Business plan	Trade expo' stand	Website	Lab work	Trade expo visit
Develop business understanding	**20**	16	13	7	10	17	**24**	15	16	**0**	17
Develop technical understanding of product	9	7	10	**21**	14	17	6	10	14	**23**	10
Improve communication skills	**5**	6	14	15	17	19	19	**23**	18	**1**	13
Develop chemical product	12	8	10	**24**	12	16	14	11	6	**22**	**5**
Application of engineering in real world	**5**	14	**4**	14	8	12	10	19	13	13	19
Good grades	10	9	12	18	18	**22**	**23**	16	**21**	14	**5**
Team organization	**4**	**1**	17	13	17	17	18	20	16	17	**5**
Develop experimental procedure	**0**	**−2**	**2**	19	6	7	**5**	**3**	**2**	**26**	**0**
Improve creativity	9	**2**	15	13	8	7	8	**22**	**22**	6	16

'Way too much work for the marks available.' 'Very practical orientation regarding workshops.' 'It was a different style of subject from what we're used to'. (second year students)

'It's interesting and different to any other course in Chemical Engineering'. 'Less workload <required> for subject.' (fourth year students)

Scoring Matrix

At the beginning of the second semester, the fourth year students participated in a scoring matrix exercise (Buchy and Quinlan, 2000). Their first exercise at the beginning of the year was to prepare a 'scoping statement' for the year ahead. This statement was designed to make them think critically about the learning objectives for the year ahead and the planned assessment. This exercise was poorly done as the students did not 'take charge of their own learning' but regurgitated what had been given to them in the introductory lecture. The scoring matrix was therefore used in conjunction with the second semester scoping statement, to get the students to evaluate the learning goals and their ownership of them.

Table 5 shows the results of this scoring matrix. Students developed the learning outcomes (vertical axis) and worked with the lecturer to develop the teaching methods (horizontal axis). Each of the 14 students rated each of the teaching methods from -1 (detrimental) to $+2$ (essential) with respect to each of the learning goals; this gave a maximum possible range of scores of -14 to $+28$. High scores represent a strong correlation between teaching methods and learning outcomes (e.g., team organization outcomes were achieved through workshops and deliverables). Low scores indicate the failure of a teaching method to facilitate a learning outcome or more likely, show that a teaching method was not designed to address a learning outcome (e.g., experimental design was not addressed by key-note or guest lectures). Both high (≥ 20) and low scores (≤ 5) have been highlighted in the table.

Most remarkably, the results show:

- the value of the proscribed assessment tasks, technical mentoring and laboratory work with respect to achieving learning goals;
- the questionable worth of guest lectures as 'application of engineering in the real world' received only 50% of the total available 28 points and other categories did not score exceptionally well either; and
- the fact that experimental procedure needs to be addressed further, probably by key-note lecture and follow-up workshop.

The spread of marks across the categories shows the need for the combination of delivery methods to achieve the learning outcomes. This is reinforced by the feedback received from the academics involved with the course and the high quality of student deliverables.

CONCLUSIONS

CPD has been introduced into the Chemical Engineering curriculum at The University of Queensland though a cohesive stream of CPD electives. This paradigm shift in learning, requiring chemical engineers to concentrate on the design, manufacture and marketing of high-value, low-volume, limited life products, has been achieved by the use of experiential, project-based courses. Of particular note are the fourth year projects that are based on cutting-edge products. This facet of the course is believed to be one of its major strengths in terms of real-world experience and application.

Initial reflections from lecturers, mentors and students show that the courses have been successful in achieving learning objectives and hence the CPD minor will continue to be offered and developed. Lecturers have observed high levels of enthusiasm and interest in the courses and this is reflected by student's comments indicating that the courses are rewarding even though they require a large amount of work. The final deliverables of both the second and fourth year courses are notable for their high quality and this further confirms the success of the course in terms of learning outcomes.

However, the courses as they currently stand do need some development. Efforts will be made to reduce the work load, give key-note lectures in experimental procedure in the fourth year, and address the laboratory/time problems experienced by the mentors, perhaps by limiting their exposure. The successful 'hands-on' focus will be maintained.

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