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LEADERS BY DESIGN: ENGINEERING DESIGN AS A TOOL FOR DEVELOPING LEADERSHIP SKILLS

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ABSTRACT
We describe the development of a new, design-centered undergraduate program in the Department of Civil Engineering at UCL. We discuss how educational aims, criteria for admission, curriculum structure and content, and faculty profile have been re-designed in an integrated manner to deliver a very specific aim: to attract students from the top 10% of the ability range, and to equip them with the skills to become leaders at international level, in academia, government, business and society. In this program, learning Civil Engineering is no longer the principal aim, but the means by which a certain set of leadership skills are learned and developed. We also discuss the results of the program and the way we are introducing industrial and international issues.

Keywords: Engineering design education, curriculum, leadership

1 INTRODUCTION: THE ELUSIVE TOP 5%
At the start of 2003, the Department of Civil and Environmental Engineering at UCL (later Department of Civil, Environmental and Geomatic Engineering, hereafter indicated as CEGE) was the weakest Department in the School of Engineering in terms of undergraduate students. Applications for places were on a long-term downward trend, and the average offer made to students was for grades C in three A-levels, typically in Mathematics, Physics and another subject. CCC was the minimum grade accepted by UCL, and was well below the typical grades in other Engineering departments at the time (ABB).

This low quality of the student intake was a more extreme aspect of a deeper problem affecting the entire School of Engineering, and to a certain extent the entire Engineering higher education in the UK and in several other countries. This general problem can be stated in one sentence: Engineering schools find it difficult to attract students close to the top of the ability range.

The issue of the comparatively low popularity of engineering and science courses in the UK was not new, and had been for years the subject of studies by professional institutions such as the Royal Society and the Royal Academy of Engineering: to take just one example, on 17 December 2003 the then Chair of the Royal Society Education Committee, Sir Alistair MacFarlane, called “for urgent action to tackle the crisis in science education and to reverse the decline in the popularity of science, engineering and technology among pupils and students.” [1] The Royal Academy of Engineering and the Engineering Council periodically publish reports on the health of engineering education and of the engineering profession, and submit evidence and analysis in response to initiatives coming from government or industry.

These analyses, and the proposed solutions, were and are however focused normally on the big picture (such as the role of culture in the low esteem in which professional engineers are held in Britain, or the effect of changes in legislation about student finance), rather than on local factors that could be altered by decision taken at department level. The CEGE problem at UCL was serious: the department found it difficult to attract average students, let alone top students. These issues had been there, to some extent, for many years, and not just in CEGE. They came to a head in 2002/03 because the number of students in the Engineering School as a whole had dropped so much that there were fears that the School, or parts of it, might become no longer viable within a few years.

A long and comprehensive review of all aspects of the School's learning strategy followed, in parallel with reviews of research and administration, culminating in the summer of 2003 in a series of recommendations that were adopted by the Dean. The recommendations were about short-term actions that could be taken within two year and were expected to have some effect within three-four years.

Coincidentally, in late 2003 a new Head of CEGE and a new UCL President were appointed. Also coincidentally, the faculty profile at that time was such that within the following two years about one third of the CEGE faculty were expected to retire. Thus, it was decided to attempt a complete re-design of the study program in CEGE, this being not only the weakest department in the School but also the one with the most immediate potential for radical change.

All aspects of CEGE were reconsidered in an integrated manner: faculty profile (for teaching and research), student profile, educational aims, structure and content of the study program. The resulting recommendations involved the spending the almost the entire surplus of the School in hiring eleven young faculty while none of their older colleagues had retired yet, thus making it possible to have a smoother transition and to dedicate more resources to the re-design of the curriculum. This non inconsiderable financial effort was accepted by all other department Chairs in the School, by the Dean, by the President and the by the UCL governing body.

2 ANALYSING THE PROBLEM

The first step in the development of the new program was to find out what was wrong with the old – that is, why it failed to attract the best students. It was known that the number of schoolchildren studying Mathematics at advanced level (and thus the number of school leavers qualified for entry to engineering programs) was dwindling, and that other, more attractive programs (especially in business studies) were attracting the best of those students, but it wasn't clear why exactly engineering programs should be less attractive than, for example, programs in Mathematics or Physics: was it "engineering the profession", a less attractive career path for engineering graduates, or was it "engineering the field of study", a less attractive academic discipline?

To find out, we interviewed some twenty schoolteachers and more than one hundred and fifty students divided into two groups. This was a kind of market research exercise, carried out in an effective but not rigorously professional manner; the desired outcome consisted of suggestions for CEGE to act upon, rather than a comprehensive study.

The feedback from schoolteachers was somewhat predictable but yielded an unexpected and interesting piece of information: that many (maybe most) pupils choose their advanced subjects more or less at random or for reasons not related to their future career or study plans. Thus, for example, not having chosen (for example) Mathematics would not necessarily indicate lack of interest or even lack of aptitude.

This was very interesting not only because Mathematics occupies a central place in the typical engineering curriculum, but also because results in Mathematics tests, even at the start of the first year at university, are the best predictor of success at exams throughout engineering programs. Since most exam questions require a good deal of algebraic manipulation, students who are not fluent in algebra find them very difficult and are often unable to complete them in a sufficiently short time. It is important to stress that is lack of fluency in algebra rather than in calculus which is the most serious handicap; thus, students with strong algebra but no advanced Mathematics are more likely to succeed than student with good knowledge advanced mathematics but weaknesses in algebra; moreover, fluency (resulting from practice in solving problems) rather than knowledge seems to be the problem. This is very important in the light of the teachers' view about the random nature of students' choice of advanced subjects: we were led to conclude that Mathematics at advanced level should not be a requirement for admission to engineering programs – but a strong performance in algebra should.

Our conversations with students yielded even more interesting feedback. Two sets of students were interviewed: UCL students who had the entrance qualifications needed to study engineering, but had applied to departments outside engineering instead; and (as a control group) UCL engineering students. Each student was interviewed individually in an informal setting.

Although both sets of students had the right qualifications to study engineering at UCL, those who hadn't chosen to do so had on average a more mixed set of advanced subjects: whereas most engineering students had taken three advanced subjects in the sciences, most non-engineering students had taken two advanced subjects in the sciences and one in the arts. This was the only significant difference between the two groups.

Non-engineering students were asked two questions. The first was: when you were in the process of choosing your university and field of study, did you consider studying engineering (for which you were qualified)? To this most students answered that they hadn't considered studying engineering because they didn't want a career in engineering. It was pointed out to them that not more than a third of our graduates work in engineering firms, while the rest work in finance, consultancy, general management; most said that, had they known about this, they might have considered studying engineering.

We then asked to look at three engineering programs in Electronic Engineering from three different universities (UCL, Imperial College and Columbia), which had been slightly edited to prevent students from guessing which universities the programs belonged to. After giving them some time to look at the list of mandatory and optional courses, we asked them to choose the programme that they thought most attractive. The collated results were as follows: one student chose UCL, four chose Imperial, and the rest (more than eighty students!) chose Columbia. Asked to explain the reason for their choice, students who had chosen Columbia gave the relative breadth of the Columbia curriculum (with about a fifth of modules from outside the main field of study and often from the arts and humanities). It is worth noting also that Imperial College had at the time a very well run humanities programme, from which engineering students could choose a few optional modules (but were allowed fewer than at Columbia).

Not surprisingly, there was a correlation between these students' preference for a broader, less technical curriculum and their choice of a "mixed" (sciences and arts) set of advanced subjects for their last two years at school. In our experience, these students may occasionally have some problems in the first year (especially with Mathematics, if they have not taken it at school at advanced level), but graduate with significantly better grades than their contemporaries who have studied science-only subjects at school.

Our conclusions from this (admittedly not very rigorous) research exercise, and from our experiences of student performance in engineering exams, were the following:

1. Schoolchildren choose their advanced subjects nearly at random, and their not having chosen science subjects says little or nothing about their potential as engineering students.
2. Those pupils who choose a less narrow curriculum at school are deterred from studying engineering at university by their dislike of an engineering career, which they perceive as too limited, and by the narrowness of the engineering curriculum
3. Those same students are also the most likely to do well in the study of engineering at university, more so than their more narrowly "technical" contemporaries.
4. In order to persuade these students to choose engineering at UCL, we would have to change our curriculum and make it more similar to the wider, less narrowly focused curriculum of US universities (as epitomized by Columbia), and to stress the very wide career spectrum available to graduates in engineering.

It occurred to us as afterwards that it would have been very interesting to interview a larger number of female students, to find out ways to increase our low female intake (which was then approximately 15%). We took the fact that female engineering students tended in our experience to do better than their male counterparts, and also to choose from a wider range of options, as an indication that a wider curriculum *might* be more appealing to female students as well.

3 DECIDING WHAT TO DO

On the strength of these conclusions, we decided to re-design the CEGE curriculum, as well as our marketing literature and our admissions criteria, as follows:

1. To change our aim from educating future engineers to educating future leaders in industry, commerce, politics and society, using engineering to help them develop the necessary skills – in order to break the link between engineering as a field of study at university and as a professional career outcome.
2. To change our admissions criteria and no longer require Mathematics and Physics at advanced level, but simply require A grades in any subjects – in order to emphasize our willingness to accept applicants with “mixed” subjects (from arts and sciences).
3. To re-design our curriculum focusing it on the solution of complex engineering problems – on design, rather than analysis, and on engineering rather than science - and on the context in which engineering problems are solved, with more attention to the societal context in which engineering operates.

None of these decisions was readily accepted either by faculty or by external engineering bodies. The objections put forward can be summarized as follows:

1. The proper aim of an engineering department is to educate future engineers. The proper aim of an engineering department in a research-intensive university such as UCL is to educate the future engineering elite, identified as research engineers. Graduates in engineering who work in, say, finance, are a loss to the profession.
2. Engineers must be technically focused, with minimum exposure to modules from outside science and engineering. Allowing them to take “outside” module requires them to drop technical modules, which makes them less technically competent engineers. Furthermore, diluting the scientific and technical content of the curriculum gives the impression of “dumbing it down”.
3. The best students for this kind of technically focused study are those who have studied science-only subjects at school.
4. How can students who have taken no advanced Mathematics – however good their algebra – perform well in engineering and science examinations? Surely they will need additional tuition!

The fallacy of the third point is obvious from exam results, where students with “mixed” advanced subjects at school achieve on average better results than their more technically focused contemporaries. As regards the second point, it suffices to note that a common complaint from engineering firms is that financial decisions are taken by accountants with no exposure to engineering – which can only change if enough engineers go on to become accountants and achieve high status in their careers!

The fourth objection is more interesting because of the special place of Mathematics as the main intellectual tool for the analysis of engineering systems. As noted earlier in this Section, Mathematics tests in the first few months of the first year are a very good predictor of overall performance throughout the program. However, as noted above, poor exam performance has more to do with poor algebra and little to do with Mathematics at advanced level.

External accrediting authorities needed some persuading before they agreed to support our experiment. Fortunately, the Engineering Council was then in the process of developing their new standards for engineering professionals (UK-SPEC: Standards for Professional Engineering Competencies [2]) which recognizes the complexity of engineering problems. UK-SPEC requires engineering curricula to cover five areas: mathematics and science; engineering analysis; engineering design; context; engineering professional practice. Thus, it was possible to show that our proposed curriculum was a better fit with UK-SPEC than more technically focused programs.

4 DESIGN OF THE NEW CURRICULUM

It was decided at an early stage that design should be the focus of the entire curriculum. The reason for this is obvious – it is in the design of an engineering product, whether it be a component or sub-system, a system, or a service, that science and analysis, professional practice and consideration of the context come together. If the development of leadership skills was to be the aim of this engineering program, then an appreciation of the complexity of problems and a bias towards solving, rather than analyzing them, earmarks design as the educational core.

The first practical question that had to be answered was: should the "non-technical" side of the curriculum be delivered to students in distinct modules, or should it "permeate" the entire curriculum, including the more technical or scientific modules?

Advice from professional bodies was in favor of separate modules, for three reasons:

1. Separate non-technical modules can be taught by specialist, thus ensuring that they are delivered seriously. The "permeate" approach is notorious for being used to create an illusion of greater curricular openness, but rarely delivers it.
2. A curriculum with well defined non-technical modules is easier to design, and each module can be modified more easily later if requirements change.
3. With separate modules it is easier to involve the outside world, and especially our business partners, in the delivery and funding of modules they are interested in.

On the other hand, we were aware that students were not very motivated to study certain subjects perceived as too theoretical, with no obvious links to engineering problems. We thus decided to adopt a compromise, using "scenarios" from real life as a "glue" between technical and non-technical subjects, to demonstrate to students how, for example, a certain equation is used in a wider engineering context, or why certain experiments have to be carried out. Furthermore, in order to emphasize the reasons why certain subjects are studies, we divided all first and second year modules into four clusters for which the common factor was not content but functionality. This is the resulting First Year curriculum [3]:

- <u>Context</u>: The Engineering Profession; Decisions in Context; Transport and Society; Sustainable Development and the Environment.
- <u>Mechanisms</u>: Biology; Chemistry; Fluids I; Materials I; Soils I; Structures I.
- <u>Tools</u>: Drawing; Geomatics; Mathematics I.
- <u>Change</u>: Design; Scenarios 1 through 4.

This is the Second Year curriculum:

- <u>Context</u>: Economics; Geology; History; Statistics.
- <u>Mechanisms</u>: Chemistry II; Fluids II; Materials II; Soils II; Structures II.
- <u>Tools</u>: Field Studies and Surveying; Mathematics II.
- <u>Change</u>: Design II; Systems II; Scenarios 6 through 8.

The last cluster ("change") is the educational core of the curriculum. The entire structure stresses that the objective of engineering is to effect change, and that this is done by design by using concrete, real-life scenarios. The term "design" here does not refer to any particular set of techniques, but to the general process of turning ideas into products and services. Examples of 2008/09 scenarios: controlling pollution and congestion in St Albans (a town North of London); designing an offshore wind farm in the Thames estuary; planning the expansion of an airport; water management in the South East of England.

5 RESULTS

The new marketing (Civil Engineering to educate the leaders of the future), admissions criteria (top grades but no subject requirements but strong Algebra) and the new curriculum were launched between 2004 and 2006. At the same time, eleven new faculty were recruited and were given the task of delivering the new curriculum. The new staff members were young and more diverse than existing faculty: about two thirds of them were female, and most were from outside the UK.

As explained in Section 2, the new recruitment criteria (high grades required but no specific subjects) were expected to attract a significant proportion of applicants with "mixed" subjects at advanced level, from arts and sciences. This did *not* happen: the majority of applicants had taken traditional subject, especially Mathematics, although with much higher grades. A few students (less than 5%) had no advanced Mathematics, but they required no additional tuition and did very well by catching up by private study with no special assistance. Their presence in the class contributed to the development of an ethos of self-directed learning that benefited all.

In the first year of the new cohort, the new curriculum was not yet ready for delivery and students were examined in the old curriculum, which permitted a more direct comparison with the previous cohorts. The examination results for the new cohort were significantly better, with higher averages and drastically reduced failure rates. It is worth noting at this point that failure rate in engineering departments (defined as the fraction of students failing to progress from one year to the next) is typically between 15% and 20%, with peaks of 20-25% in some departments. In CEGE, the failure rate dropped to below 10% for the first time in many years, *without* any benefits from the new curriculum (which had not been introduced yet).

The following cohort (2007/08, examined last summer) showed an even more marked improvement in terms of qualifications at entry and of exam results. Interestingly, all other engineering departments (which had not changed their admission criteria and had not re-designed their programs of study) had experienced an improvement in entry qualifications, although less pronounced, *but no significant improvement in their failure rates*. Clearly, the new Civil Engineering cohort had not just higher entry qualifications, but also different expectations and motivations – although this is just conjecture from their much improved exam results.

Even more interestingly, the new Civil Engineering cohort is approximately 45% female, well in excess of the 15-20% previously typical of Civil and still the norm in all other engineering departments. This is in our view partly the result of our new emphasis on leadership in any field of endeavor rather than excellence in a specific engineering discipline, partly to the example of a faculty which is now about 50% female.

6 ONGOING WORK: PARTNERSHIPS WITH INDUSTRY

A design-centered curriculum, where "design" indicates the process of turning ideas into services and products needed and wanted by society (and is almost synonymous with "engineering") implies a strong connection between the academic curriculum and the outside world. After all, the whole point of re-designing the Civil Engineering curriculum was to relate what for engineers are intellectual tools, such as mathematics, to "real life" problems through design project and scenarios.

This, however, is only part of the story. In order to be "real life", scenarios should ideally be provided by the world outside academia – especially, of course, engineering companies and their clients. All UCL departments of engineering have business partners for certain areas of applied research, but these partnerships do not normally influence teaching directly. This is something that we have not yet been able to do at undergraduate level; however, at graduate level we have experimented with an innovative form of industrial partnership that (we hope) will provide a departmental focus for students to be exposed to real-life engineering work.

UCL has formed a partnership with the Canadian company Arius 3D [4], which produces a very advanced color laser for the three-dimensional scanning of physical objects. This has resulted in the installation in the UCL Chorley Institute of the latest generation 3D color laser. Based on National Research Council technology licensed to Arius 3D, the laser was the first of its kind in Europe, and has already generated more than £ 2.5 million of research funding proposals, as well as numerous workshops and seminars.

Arius 3D has provided associated software to UCL, as well as specialized scanning training to UCL staff. The company has considerable experience in working with universities and has collaborated with UCL in a number of projects, which include the scanning of artifacts in the UCL Petrie Museum of Egyptian Archaeology. The scanning activities have stimulated UCL contact with other institutions such as the British Museum, and 3D visualizations have attracted attention to our graphics animation computer science teams, with games and entertainment industries, advertising companies and the media expressing interest in new visualization technologies.

The unique character of this partnership is that the Arius 3D laboratory in the Chorley Institute is both a university laboratory and an industrial laboratory, which has the potential to expose graduate students much more closely than usual to industrial research. It is hoped to introduce similar partnership in other areas of engineering, and to extend the use of the facilities thus established to a wider proportion of students, including undergraduates.

7 ONGOING WORK: INTERNATIONAL ISSUES

Another aspect of our students' exposure to the outside world is the international side of engineering. Our students are more than 35% from outside the UK, and so are a majority of our faculty staff members. Engineering is practiced very differently in the UK and, say, in France or in Japan, and we feel that our students should be exposed to this diversity, to enable them to function in a truly international context – which most of them will have to do anyway.

Like most universities, we have some exchange programmes with partner universities overseas, whereby our students can spend their third (penultimate) year studying engineering in a different culture and often in a different language (in which case students are offered language tuition as appropriate in their first and second year). This is a very valuable experience for them, because the education, training and approach to problem solving are somewhat different in a British, French or Japanese engineer and a lengthy exposure to a different learning style can be very beneficial.

This kind of arrangement has two drawbacks. First of all, international exchanges must be roughly balanced, i.e. the number of students going on exchange from A to B must be roughly the same as the number of students going from B to A. Thus, a partner university with low outgoing flow effectively limits the incoming flow, and depending on which departments are covered by an exchanges, numbers can be tiny. Throughout the Engineering School at UCL, there is latent demand for year abroad study from about 10% of the student body, of which only about half can be accommodated by our partner universities. A further limit is that few UK students can speak a foreign language, and thus very few can go to continental European universities.

The result of these limitations is that only a small fraction of our students (about 5%) can benefit from an exposure to a more international flavor of engineering. Thus, we are considering something different: a year at UCL where *all* students are exposed to a culturally different engineering experience without leaving UCL. For example, a set of students could take all their modules in French (being taught by UCL faculty who are French nationals), be assessed in French, and learn about the way engineering works in France – about the economy, legal system, regulatory framework and business culture in France. An experimental "year abroad at UCL" of this kind will be launched next year for Japanese engineering, to be followed – if successful – by similar programs for other major cultures.

8 CONCLUSIONS

The new program of study in the CEGE Department has been designed to educate future leaders in engineering, business, academia and in society in general, and to attract students close to the top of the ability range. The programme is centered on design scenarios and relies on admission criteria which requires very high grades but no specific subjects.

The program has been very successful in attracting very able students. With the old program, the average entry grades were just over CCC and the typical first-year failure rate was between 15% and 20%; now the average grades are above AAB, and failure rates about 5%. The student cohort has also an unusually high proportion of female students (about 45%) and is very international in terms of nationality and outlook (with the highest proportion of students in the entire university wishing to spend one year of study abroad).

To be sure, other factors have contributed to this positive result; in particular, the closing down of two other departments of Civil Engineering in London contributed to an increase in applications, by reducing the options available to students. However, having considered other departments (not only of Civil Engineering) in similar situations, we are confident that the new approach to student recruitment and the new curriculum have been critical factors in attracting a much better student cohort.

There are, however, other factors that should be considered. For one thing, "leadership" skills are not easy to either define or teach. The highly successful leadership program at the Said Business School at the University of Oxford is designed on the assumption that leadership rests on the twin pillars of *rhetoric* (the ability to persuade others to trust us) and *practical judgment* [5]. For now we have concentrated on the latter, which of course leaves much of the field of interpersonal skills unexplored.

When we say that the new curriculum is centered on *design*, by this word we mean the entire process by which ideas are turned into products and services that satisfy societal and business requirements, with an emphasis on systems and on real-life problems. We have given scarce emphasis to the *qualitative and aesthetic* aspect of design – a significant omission, which we plan to remedy in the future. It is important to remember that much of the success of any design relies on the emotional response to it by its users, and this is determined by its look and feel as much as by its functionality. Furthermore, it is useful to remember that great design in the past did *not* rely on Mathematics and Physics nearly as much as modern designs do; triremes and cathedrals were designed by a much more qualitative and experimental process, of which we know little.

Finally – the ultimate success of a program is measured not by its adherence to good practice, nor even by its short-term success in producing successful, employable young graduates, but by the long-term success of its graduates, ten, twenty of fifty years later. In the past, we have been successful in educating successful research engineers; our success (or lack of success) in educating engineering leaders lies a long way in the future.

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This paper refers to internal UCL documents submitted by internal committees and occasionally to external bodies, but never published. The authors will be happy to consider requests to supply documentation in compliance with UCL regulations and with current legislation.

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