Engineering Programme Design

Solving a Constrained Optimisation Problem

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Conference Key Areas: Curriculum Development, Sustainability

Keywords: Programme Design, Constraints, Resources, Optimisation

INTRODUCTION

In one way or another, the majority of engineering programmes are accredited by professional bodies. In Ireland, the accrediting body is Engineers Ireland and quadrennial programme assessments are conducted by independent panels established by Engineers Ireland, using published accreditation criteria [4]. These accreditation criteria are based on quantifiable Programme Outcomes (POs), and each programme should be able to demonstrate that its graduates achieve these POs. Engineers Ireland has established the following POs for professional engineering programmes:

(a) Advanced knowledge and understanding of the mathematics, sciences, engineering sciences and technologies underpinning their branch of engineering.

(b) The ability to identify, formulate, analyse and solve complex engineering problems.

(c) The ability to perform the detailed design of a novel system, component or process using analysis and interpretation of relevant data.

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(d) The ability to design and conduct experiments and to apply a range of standard and specialised research (or equivalent) tools and techniques of enquiry.

(e) An understanding of the need for high ethical standards in the practice of engineering, including the responsibilities of the engineering profession towards people and the environment.

(f) The ability to work effectively as an individual, in teams and in multidisciplinary settings, together with the capacity to undertake lifelong learning.

(g) The ability to communicate effectively on complex engineering activities with the engineering community and with society at large. (Engineers Ireland)

Accreditation based on outcomes is relatively new. Previously, engineering programmes were accredited based on defined input criteria. A brief review of accreditation criteria, preceding outcomes-based approaches, shows that minimum requirements were set by accrediting bodies. These minimum requirements typically included (i) “qualified, forward-looking and competent faculty; (ii) a defined curriculum (based on engineering discipline) that prescribed specific subjects and minimum durations for those subjects; (iii) quality and performance of the students on the programme, including intake quality; (iv) critical facilities to support the programme, including classroom space, laboratory space, workshop space, library, etc. [5]. Therefore, in order to design and run engineering programmes, defined levels of resources were quantifiable and required in advance. This made programme design simpler, albeit it resulted in the design of programmes to meet minimum accreditation criteria. For example, in 1982, Engineers Ireland [3] set down the following input criteria to assess the standards of engineering programmes.

(a) Minimum entry standards; for example minimum student entry standards in mathematics

(b) Course philosophy: which is a general statement on the objectives of the course

(c) Course content; including requirements for contact hours, projects, content, design, etc.

(d) Course duration; specifically a minimum number of years of study, e.g., 4 years

(e) Staffing; specifically guidelines on number, experience, and qualifications

(f) Facilities; which is a general statement on necessity of adequate facilities

(g) Assessment methods; which is the requirement to assess each and every student

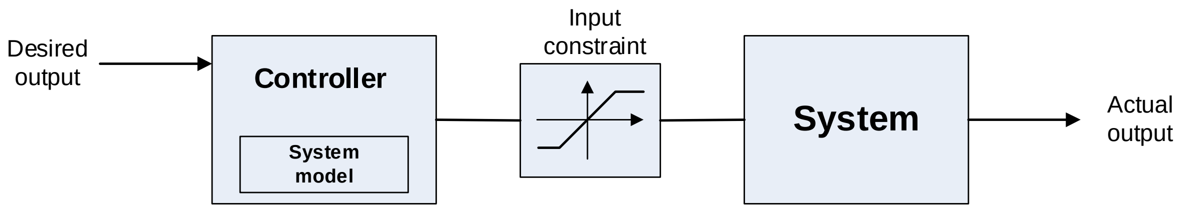
(h) Accreditation; which describes a necessary formal accreditation process.

With accreditation based on input criteria, the philosophy is that quality assurance on each of the inputs (such as minimum entry standards, minimum number of hours of study, required assessment, formalised accreditation processes) provides evidence of the quality of the programme. Modern engineering accreditation criteria, based on programme outcomes, rather than defined input parameters, are intended to provide greater latitude and freedom to engineering programme designers, while also focussing on the abilities of the graduates emerging from the programme. With accreditation based on outcomes, institutions are not measured on the basis of a set of necessary inputs, they can be innovative in programme design but must be able to provide evidence that graduates meet the POs for their programme. These POs can be tailored to institutional goals and the academic environment in which they will be delivered. In Ireland, "the pedagogy and method of delivery of programmes is left to the HEIs." [4].

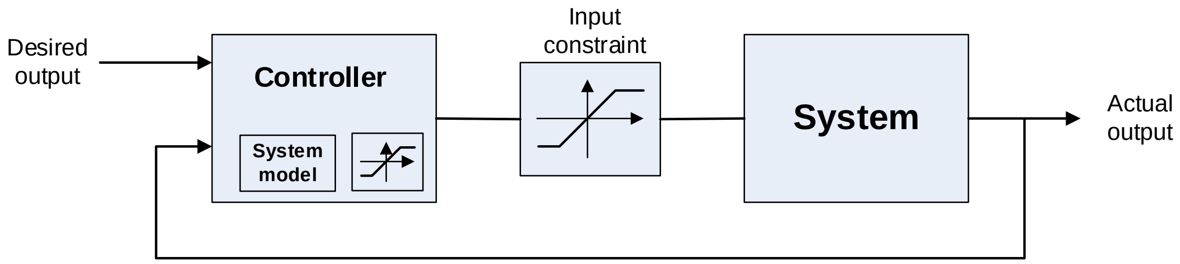
The latitude afforded by POs, rather than defined input criteria, has meant greater freedom with regard to programme design. But, perhaps not surprisingly, less prescription in terms of defined input parameters can lead to programmes which are designed without taking appropriate *a priore* account of resource limitations to deliver the programme. Resource limitations equate to constraints and they clearly have an impact on whether the engineering programme achieves its PO objectives. We will examine this in more detail using a control systems analogy.

1 CONTROL SYSTEM ANALOGY TO ENGINEERING PROGRAMME DESIGN

The concept of designing an overall system with (and without) knowledge of constraints, which apply at various points in the system, is well-known in control systems design. In most real systems, including educational systems, there are inevitable constraints on the resources, or effectors, which can be brought to bear to affect the performance or throughput of a system. In Figure 1(a), the output of the controller is constrained by the input constraint (the saturation block) which follows, resulting in a non-optimal input to the system designed to bring the output to the desired value. Within the control systems community, control philosophies have been designed [e.g., 7] to allow the controller to take account of not only the dynamics of the system (via an internal mathematical model of the system), but also the constraints to which the control signal may be subjected. This is usually achieved through the solution of a constrained numerical optimisation problem and recognises the fact that a constrained optimal control signal (where the constraint is subsequently applied to a control signal determined for a system with no constraints) is not as effective as an optimal constrained solution. In essence, not only will the optimal unconstrained solution waste control effort which cannot be transmitted to the system, but the system response will also be inferior to the control calculation which recognises the presence of the constraint in advance.



(a) Controller has no knowledge of input constraints



(b) Controller is aware of input constraints

Fig. 1. Analogy of control system designed with and without knowledge of constraints

In this spirit, we address the design of engineering education programmes, where constraints (especially resource constraints) are an inevitable reality and our mission is to make the best of the limited resources available. This, however, is in contrast to the bulk of published studies [e.g., 2, 9, 10] on engineering programme design, which assume a somewhat idealised situation of unlimited resources.

2 ENGINEERING PROGRAMME DESIGN

An engineering programme is designed using the core resources of (i) staff; (ii) space; (iii) equipment; and (iv) materials. An engineering programme requires all of these core ingredients, and is either designed knowing that they are available, or assuming that they will be made available, see figure 2 below. The global and local economic environment acts as an uncontrollable influence on these resources, resulting in constrained inputs to the Learning Environment. The learning methodology (which is ultimately supported by the learning environment) is informed by the desired learning outcomes for the programme, which provides the major design input to the programme and cognizant of external requirements, such as professional accreditation criteria. It is also influenced by, and must take account of, the number and quality of the students who will be in the programme. The objective is to implement an optimal learning methodology to achieve the desired learning outcomes, for the given quality and characteristics of a typical input student cohort, mindful of the resource constraints that the learning environment is subject to.

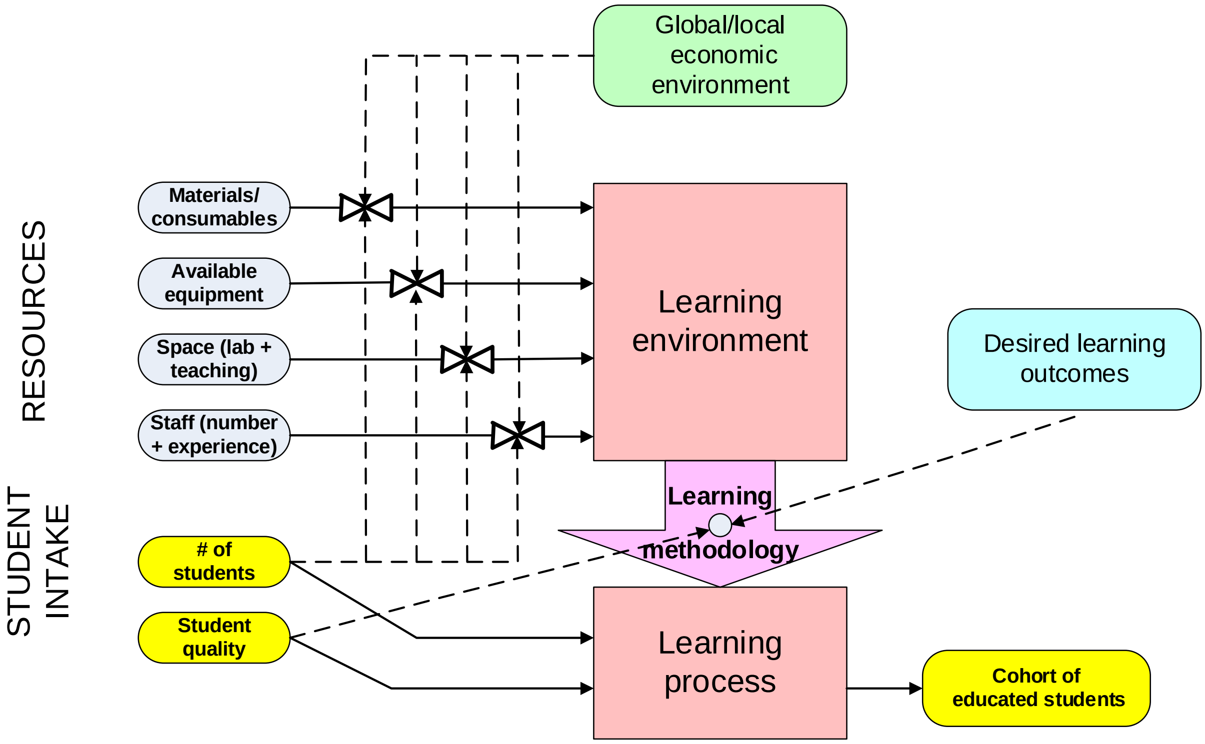


Fig. 2. Programme Design as a Control Process

Table 1 defines the available resources (appearing on the top left of Fig.2), and each is discussed in more detail below the table.

Table 1. Programme Resources

Input	Description
Staff	This represents the experience and competences of the faculty who will be available to teach on the programme. It also represents the actual quantum of hours required to deliver each stage / year of the programme. While it also includes technical support staff, we will not explore detailed technical staff competences in this paper.
Space	This represents the space availability in terms of lecture rooms, study rooms, laboratories and workshops.
Equipment	This represents the type of lab and workshop equipment available for each year of the programme.
Materials	This represents the teaching materials, lab consumables, etc. It also includes books that can be made available, and on-line subscriptions for access to discipline-specific resources.

2.1 Staff

In an ideal world, all academic staff would be capable of teaching all courses on the programme being designed. Thus, an electrical engineering faculty member would be able to teach circuit theory, electronics, telecommunications, controls, power systems, signals, maths, etc. Notwithstanding the brilliance of faculty, there are usually some clear constraints on their teaching flexibility. For example, there may be only one person who can teach Fields & Waves at advanced undergraduate level. There may be junior faculty who should be asked to teach only first or second year students. There may even be a senior faculty who may have less aptitude to engage first year students. Postgraduate students may be available, but are generally most appropriately employed for laboratory or tutorial sessions.

An objective observation on Ireland over the past 6 years is that many experienced teaching faculty have retired early, leaving schools of engineering with difficult-to-fill gaps in disciplinary expertise, as well as a general reduction in teaching experience. This has been due, in significant part at least, to incentivised early retirement

By quantum of hours we mean the hours necessary to deliver each year or each stage of the programme being designed. In some universities, the input quantum is teaching hours per faculty member. In other universities it is faculty load: the number of courses that a faculty member will be asked to teach.

Taking a simplistic view, if a 4-year engineering programme has 6 courses per semester over a total of 8 semesters, that equates to 48 separate courses to be taught. If the university is a teaching-oriented university and has a faculty teaching load requirement of 6 courses per faculty member, then 8 full-time faculty are required – at a minimum – to cover all of the required 48 courses. If the university balances teaching load with research outputs, the teaching load requirement might be reduced to 4 or perhaps 3 courses per faculty member. This increases the minimum number of faculty required to 12 full-time faculty, or 16 full-time faculty, respectively.

These minimum faculty requirements can be moderated by introducing a work placement component into the programme. In this case, the teaching requirements for one semester, or even a full academic year, might be replaced by the need for a work-placement coordinator, who may or may not be a faculty member. Note that in programmes with a study-abroad, or Erasmus component, the goal for the programme should be a balanced flow of students inbound and outbound, with therefore no net effect on the number of faculty required to teach on the programme. Other adjustments to faculty time/course requirements include major individual projects, normally undertaken towards the end of the programme. This, of course, brings associated supervision requirements which may or may not ease the faculty time commitment, compared to a more traditional course.

Finally, we make the observation that project-based learning also typically involves a greater time commitment than traditionally-taught courses, though the resource implications are rarely discussed [8].

2.2 Space

This represents the space requirements in terms of lecture rooms, classrooms, study rooms, laboratory facilities, design spaces, and workshops required to deliver the programme. Space is often viewed as a prized resource, and is often hoarded within universities. Different universities operate different policies with regards to space. In many universities an engineering college or school will ‘own’ its own space, and decisions regarding its allocation will be made at an appropriate devolved level, often by the Dean or by a committee established by the Dean. In some universities, colleges and schools are ‘charged’ for each square metre of space they ‘own’. Space norms can be used to begin to allocate space more transparently based on independent measures of how space is utilized across the higher education sector. For example, Dublin Institute of Technology (DIT) uses Australian norms [1] to inform its central decision making with regard to decisions on space.

We also note that some space is more flexibly allocated (e.g. teaching classrooms) than others (dedicated discipline-specific laboratory space), so the rate at which the constraints can move on these different space types may also vary.

Engineering programmes use a mix of different types of space. New programmes are generally now designed with a range of active pedagogical methods, such as flipped classrooms, more team-oriented design spaces, etc., which generally require flat rooms with flexible furniture. More traditional engineering programmes will have a greater use of lecture hall space, which is often comprised of a stepped floor with tiered seating. Lecture halls have a lower space requirement, and require approximately 1.5 square metres for each student. Seminar / tutorial rooms require approximately 2 square metres per student, while design studios require up to 3 square metres per student [1].

The space norms for engineering laboratories varies considerably based on the engineering discipline involved. Civil, mechanical and chemical engineering will generally require approximately 15 square metres per student; whereas electrical / electronic engineering has a lower space requirement of approximately 7.5 square metres per student.

Lecture halls can be designed to handle large numbers of students safely, and one academic is all that is required to deliver these lectures. So lecture halls are efficient with regard to the constraints of hours and space. On the other hand, programmes that embed active learning such as project-based learning (PBL) elements into the programme will require more space resources.

Each laboratory can generally be equipped to deliver at most two, or perhaps three, different courses within the engineering programme. In addition, for health and safety reasons (H&S), most labs and workshops have fairly rigid guidelines on the maximum number of students per lab session. Within DIT, maximum student numbers are generally set at 16 students. There will also be a requirement to have a technical officer to support the laboratory, and depending on programme need, there will be an academic staff member present.

2.3 Equipment

By equipment we mean all the desired equipment for laboratories and workshops. The nature of the equipment can place additional burdens on the other programme resources. Depending on the subject and the discipline, the equipment can be light or heavy. For example heavy machine equipment for mechanical or manufacturing engineering can often only be accommodated on the ground floor or basement level of buildings. Such equipment may also make heavy demands on materials in their day-to-day operation. There will be staff implications associated with meeting minimum health and safety requirements, when students are using the lab and workshop equipment. Bigger equipment is generally more expensive than smaller equipment – it is cheaper and easier to resource a programme employing millivolt equipment rather than kilovolt equipment. There is also evidence that hardware-based labs are now being replaced with software-based labs. While the authors have not seen evidence of either improvements or deterioration of student learning in software-based labs, there are anecdotal indications that software-based labs generally have well-designed lab scripts and exercises. Balancing this is the view of some experienced academics that ‘hands-on experience in the laboratory’ is an essential part of the development of the engineering graduate.

Maintenance contracts and replacement schedules, especially for computers and computer-based equipment, should also be factored into the cost of designing and delivering engineering programmes. For new programmes, equipment costs are major considerations (constraints) while, equipment issues are less impactful on the re-design of programmes which already have an equipment allocation, mindful of any replacement/maintenance requirements or any additional needs.

2.4 Materials

This represents the teaching materials, lab consumables, etc. It also includes books that the library might require, and on-line subscriptions for access to discipline-specific resources. The actual euro value on materials that will be consumed in a lab per semester is highly dependent on the type of lab and the engineering discipline.

3 EXAMPLE 1 – DESIGNING A NEW ENGINEERING PROGRAMME

Let us assume that an engineering department in a practice-based, teaching-oriented university wishes to submit a proposal for a new engineering programme to the Dean of Engineering. The Dean establishes a Programme Design Committee (PDC), and asks for a detailed proposal and notes that it would be helpful if there were unique characteristics about the new proposed programme.

3.1 Approach 1:

The PDC is enthusiastic with the Dean’s response and full of excitement that it has the Dean’s full support. It meets immediately to begin the design of a programme that fully utilizes active learning and new knowledge from learning sciences. Consequently, the PDC takes the brave decision to design ‘from a blank sheet of paper’ with regard to the resources that it will require. They reason that this will be an issue for the Dean, and he seems to have already indicated his approval. They embark on a programme design characterised by Figure 1a, in which they are completely unaware of input constraints.

The PDC quickly decide the parameters of the programme. The structure of the programme will be 8 semesters over 4 years. The format will be a standard 6 courses at 5 ECTS per semester, for a total of 60 ECTS per year and 240 ECTS for the programme. Work placement for Semester 2 of third year will be mandatory, as will a final year project worth 30 ECTS in total across semesters 7 and 8. The target class size will be 32 students per year. This will be the optimal size for the learning environment that they wish to create, and will allow them to break each class into two groups of 16 students for flipped-classroom sessions.

Given their objective to design a completely new type of engineering programme, the PDC begin with the structure of 1st year, and propose a flipped-classroom approach for all six courses in each semester. They propose four supporting labs in each semester, each of three hours duration. For health and safety reasons, only 16 students can be supervised at one time in a laboratory by one staff member. The six theory courses will each have one lecture hour for all 32 students, and then the class will be broken divided into two groups for the balance of 6 classes at 2 hours each. Thus student timetabled hours will be 30 hours per week. This generates a teaching requirement of 54 teaching hours per week for 1st year, or 3 additional academic staff members.

With a room size capable of taking the 32 students in 1st year, this room will be sufficient for all the flipped classroom theory hours for both groups of 16 students, but the classroom will be timetabled for 30 hours each week. The PDC will coordinate the four 3-hour labs with the theory classes, and believe these can be accommodated within existing Physics, Circuits and Electronics laboratories. Thus, there should be no need for additional equipment, and class materials will be modest. The PDC propose a budget of €5,000 per annum to cover class materials for the 1st year students. They also propose that a team of two graduate students be asked to write lab scripts, under the guidance and direction of the PDC, in order to ensure that the desired 1st year Learning Outcomes are embedded within the timetabled 12 hours of practical work. Each laboratory is also supported by an experienced technical officer.

They repeat the design process for 2nd year. The bottom line is that it will still require an additional 3 academic staff members and also another flexible flat classroom. Class materials will be as per 1st year. For 3rd and 4th year, the PDC embeds more design emphasis within its planned courses and final year capstone project. Notwithstanding this, the resource requirements grow and an additional 5 academic staff are required over the two years. Also two new dedicated flexible rooms, and a dedicated final year new project lab is proposed with dedicated technical officer support and an annual budget of €10,000.

When the PDC report to the Dean, they emphasise the new pedagogical approaches embedded from Day 1 through graduation within their curriculum. They refer to the literature that supports their innovations and they confidently predict that the programme will be a huge success, and will provide the college with a reputation of being a new and exciting place to study engineering. The Dean notes this and asks for the resource requirements. The PDC provide their assessment:

- 11 new academic staff

- 4 dedicated flexible furniture classrooms
- Dedicated project studio for final year students
- €25,000 annual budget for class materials
- Heavier load on existing labs and the technical officers who support the labs
- Two graduate students to help write lab scripts and then support the labs

The Dean thanks the PDC for its hard work and cutting edge proposal, and states that the proposal will be given very careful consideration over the coming weeks and months. The proposal will be discussed in the near future with the VP – Academic. One year later, the PDC had still not received a formal response to its proposal.

3.2 Approach 2:

While the PDC is enthusiastic with the Dean's response, it is cautious regarding resources and so meets to discuss likely resource requirements as a matter of priority. The PDC realises that there may be ambiguity between what they ideally want to achieve in the new programme and the resources that the Dean may actually be able to provide. So the PDC develops some programme design approaches, including a 'blank sheet of paper' approach, and requests another meeting with the Dean in order to discuss these. At this meeting it becomes clear that there simply will not be the resources for an entirely new programme utilizing all new resources. Instead they learn that:

1. The College receives a substantial portion of its 'income' from the university based on the number and type of students it has enrolled on engineering programmes. For every student enrolled on a non-lab based programme, the College will receive €10,000 per annum. If a student is enrolled on a programme that has 'elements of lab, studio, or fieldwork' then the College will receive the unit amount (€10,000) multiplied by a weighting of 1.3, giving an 'income' per student of €13,000. If the student is enrolled on what is clearly a lab-based programme, then the weighting is 1.7, representing €17,000 in income per student. The Dean succeeds in ensuring that the PDC understands that more students equals more income, and that lab-based programmes generate more income (and incur more cost) than a mixed mode programme.
2. The Dean reminds them not to forget that the university has a global policy that no programme should exceed 24 timetabled hours per week. The PDC thinks it can live with this, but is concerned that it might limit the flexibility of their optimal programme design.
3. The Dean says that funding is available and approval obtained to recruit two new academic members of staff, and that these will not be recruited as tenured professors, but as junior tenure-track assistant professors. The Dean notes that the PDC proposal will be an important input into the type of assistant professor to be recruited. The PDC is worried, as they thought their approach created a winning argument to recruit more experienced engineering academic staff, but realises that two new academic staff is all they will get.
4. If the PDC submit an acceptable proposal, and it gets approval from Academic Council, then the Dean will allow the reconfiguration of one classroom with fixed

furniture into a dedicated design studio for the students on the new programme. The PDC wanted one dedicated design studio for each year of the programme, so only getting one in total is disappointing.

5. The Dean promises to look favourably on other requests associated with change of use for existing labs and workshops.

6. The Dean notes that discretionary budgets are getting tighter every year, and that the PDC should be aware of this and keep its proposed consumable budget as reasonable as it can, perhaps using a target of €5,000 per lab or workshop for materials.

7. Finally, the Dean reminds the PDC that, while the university has a solid reputation and is considered to be competitive regarding student recruitment, it recruits average engineering students and that 1st year attrition across the College averages 20% and on-time graduation rates are approximately 60%. The new programme should seek to improve on these statistics.

The PDC leave the meeting in a less enthusiastic mood than when it entered, and regroups over coffee to consider the constraints that it faces. One of its members states that the task is impossible, resigns and leaves. The group that remains, one of whom is a control engineer, realises that it is looking at a design problem under input constraints. She sets about to explain what she means to the other members and over the next few minutes blocks out a diagram very similar to Figure 2 above. The PDC realise that clarity on their input resources, combined with rudimentary insight into the likely student intake, provides them with sufficient information to begin to design their programme.

They begin by recognising that the incoming cohort of students may not be academically very strong, and therefore that they should be supported as much as possible in 1st year, with decreasing levels of support in subsequent years. This is also aligned with the reality that the two new academic recruits should only teach on the 1st and 2nd year of the programme initially. They set out the skillsets of the two new academics who will best suit their requirements to provide later to the Dean. The PDC agree a notional allocation of 30% of available teaching resources for the programme in both 1st and 2nd year, with this dropping to 20% in 3rd and 4th year. With maximum contact hours set at 24 per week, they begin with a scaled contact hours approach with 24, 20, 16, and 12 hours in 1st, 2nd, 3rd and 4th year respectively. They next decided that since they did not have the resources to create all new courses, they would use approximately 50% of existing and relevant (and traditionally delivered) courses over the four years.

The target class size was chosen as 66. With an estimated attrition of 10% after 1st year, this provided a balance between income from student numbers and anomalies in the group sizes for flipped classrooms. Each flipped classroom group would be comprised of 20 students. With the larger class size, the PDC believed that they would be able to convince the Dean to recruit industry-based adjunct lecturers to support their practice-oriented programme.

In designing the programme, the PDC surveys the existing teaching space, and decides on one classroom that is large enough and flexible enough to be able to accommodate two flipped classroom groups of 20 students each. Minor modifications will allow multiple projectors and white boards. This, together with appropriate timetabling into existing classroom space, will take care of space requirements.

The PDC complete their programme design, focussing significant attention on the first two years of the programme. They reason that, with students enrolling one year at a time, they will have the opportunity to re-visit what is working and finalise their designs for 3rd and 4th year. The PDC meet with the Dean to present their proposals, and receive approval to proceed through the university quality assurance procedures.

4 CONCLUSIONS

It is not surprising that lecture-based higher education is so common: it is well understood and it is the low-cost model. Curriculum reform, particularly employing results from learning theory demands more resources, especially in terms of time and space. Yet these resources are limited and there are often hard constraints on new resources. One key issue for programme chairs and department heads is to understand the resource model employed by the university, in order to understand how best to maximize resources based on student numbers.

Curricular reform, rather than individual course reform, is an expensive proposition. Active learning, such as via PBL or flipped classroom approaches, is resource intensive. To balance this, a programme design committee must be innovative with respect to how it will utilize resources. Knowing the input design constraints at the outset allows for an optimal programme design in the presence of these constraints.

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