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A curriculum framework for flexible engineering degrees in South Africa

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ABSTRACT: South Africa produces too few engineers to meet its development needs. The number of graduating engineers is slowly increasing, but is still only about 2000 per year, serving a population of over 50 million. Data from the Council on Higher Education (CHE 2013) show that for the 2005 cohort of BEng students nationally only 25% obtained an engineering degree in the regulation time of four years, with another 19% taking five years. In a study for the Engineering Council of South Africa on improving throughput (Fisher 2011), one suggestion was to increase curriculum flexibility to better cater for the needs of a diverse student population. As part of a CHE project, we developed exemplar curricula for engineering degrees designed to take either four or five years to complete. In this paper we describe the underpinning principles that guided the design and illustrate how they are applied in curriculum exemplars for a mechanical engineering degree.

1 Introduction

Engineers are vital for South Africa to meet its social development and economic goals. Yet the ratio of registered engineers to population is a very low 1:3166 in South Africa, compared with 1:543 in Malaysia, 1:389 in the USA and 1:130 in China (Lawless 2005). A contributing factor to this low ratio is the poor throughput rates of students in engineering. Analysis of data by the Council on Higher Education (CHE) for the 2005 cohort of students who registered for a bachelors degree in engineering (BEng)[1] shows that only 25% of students completed the degree in the regulation time of four years, another 19% completed in five years and a total of 55% had graduated after six years. The figures for historically disadvantaged black African students, many of whom come from impoverished communities, are 11% completed in four years, another 16% in five years and 41% had graduated after six years. There are thus both developmental and social justice reasons for South Africa to find ways to improve throughput in engineering degrees.

In 2011 the Engineering Council of South Africa (ECSA) commissioned a study on how to improve throughput in the BEng degree (Fisher 2011). The report identified seven “levers of change”, one of which is curriculum that is, “flexible enough to cater successfully for a diverse student intake”. The report states,

> …the curriculum, in particular its rigid course structure, heavy course load and lack of differential entry points and flexible pathways, caters poorly for a diverse student intake, with negative consequences for student outcomes (pg 126).

[1] Also called a BSc (Eng) or BIng

South African engineering curricula are particularly rigid in that courses are largely prescribed, with the result that students have few, if any, opportunities to choose elective courses during their degree programmes. Apart from the negative consequences for students from less privileged backgrounds, rigid curricula provide little space for innovation and adaptation to 21st century workplace demands. In its 2012 publication, the Royal Academy of Engineering states,

> A series of reports from The Royal Academy of Engineering…has demonstrated that change in undergraduate engineering education is urgently needed to ensure engineering graduates remain equipped for the new and complex challenges of the 21st century (p 2).

The report identifies four common features of successful change, one of which is, “the extent to which the change is embedded into a coherent and interconnected curriculum structure.” In South Africa, a consequence of the poor throughput rates is that the large majority of engineering students do not follow a coherent curriculum, as they repeat certain courses at the same time as they continue with courses at higher level for which they have met the prerequisite requirements. This problem extends beyond engineering, and is true of all degree programmes in South Africa. For this reason, the CHE established a task team to consider the implications of creating flexible curriculum structures that would allow students to proceed at different rates but still follow coherent curricula[2]. Four working groups were established to create exemplars in different fields of how the curricula might be structured if the majority of students were to plan to spend one year longer in the degree programme, enabling them to take additional courses for development or enrichment, while still allowing a minority of well-prepared students to complete the degree in the existing regulation time.

In this paper, we describe two curriculum exemplars devised for the BEng degree, specializing in mechanical engineering, starting with theoretical perspectives and design principles. Two of us are engineers and engineering educators, one is a physics educator and curriculum specialist and the fourth is a higher education and curriculum specialist.

2 Curriculum as a means to overcome systemic traps

The problem of low throughput rates is systemic and should therefore be addressed at the level of the higher education system. However, systems can malfunction. In her insightful book on systems theory, Donella Meadows (2008) identifies eight problematic system behavior “archetypes” that she labels “traps” because, she says, “Blaming, disciplining, firing, twisting policy levers harder, hoping for a more favorable sequence of driving events, tinkering at the margins — these standard responses will not fix structural problems.” Four of these traps are:

> **Trap 1: Drift to low performance**
> When performance deteriorates over time it is easy to lower expectations. The solution is to set absolute standards, which may be enhanced as attention is focused on the best in the system instead of the worst.
>
> **Trap 2: Shifting the burden to the intervener-Addiction**
> This occurs when a policy or the action of an individual leads to short-term relief but does not solve the underlying problem. The need for short-term action escalates, but the problem remains. The best solution is to avoid getting into the trap. The next best is to identify the underlying problem and seek long-term restructuring rather than short-term relief.

[2] The report of this task team is due to be published in May 2013.

Trap 3: Rule-beating

The imposition of rules may lead players in the system to appear to follow them but actually cause distortion of the system. The solution is to create rules that release "creativity not in the direction of beating the rules, but in the direction of achieving the purpose of the rules."

Trap 4: Seeking the wrong goal

When the indicators used to measure the attainment of goals are defined inaccurately or incompletely the system may produce unintended or undesirable results. For example, "if the quality of education is measured by performance on standardized tests, the system will produce performance on standardized tests." This may or may not correlate with quality education. The solution is to take great care in specifying indicators and goals, and to not confuse effort with results.

In trying to address the problem of low throughput rates, higher education institutions can easily fall into these traps. As the number of students who have to repeat failed courses increases, there is a temptation to lower standards (trap 1). As ever-increasing numbers of students bang on the doors of higher education, it is tempting to allow more and more students to enter, hoping that more entering students will mean more successful students, but then leave them to their own devices, to sink or swim (trap 2). Stringent requirements for programme accreditation may lead departments or institutions to comply with written criteria while not, in practice, offering courses that are well-designed or taught and therefore do not lead to effective learning (trap 3). And merely looking to increase the number of graduates can lead to graduates that have little to offer society or employers (trap 4).

Carefully designed curricula can provide a way of avoiding these traps. In referring to successful "programmes of change", the report of the Royal Academy of Engineering (2012) states,

> Almost without exception, successful and sustainable change starts with a fundamental assessment of the curriculum-wide goals and involves a high-level re-alignment of the entire curriculum structure in which a cross-section of faculty are involved. This successful approach to educational design appears to be independent of the scale of change undertaken. Indeed, most successful 'curriculum-wide' changes typically only involve the creation of a relatively small number of new courses—usually less than 20% of the curriculum. What distinguishes them, however, is the extent to which the changes are interconnected within a re-designed coherent curriculum structure with multiple horizontal and vertical dependencies (p2).

The broad curriculum-wide goals we propose are:

1. To create a pool of engineers who, taken as a whole, have a range of knowledge and skills that will address a range of needs in South Africa;
2. To allow students with diverse entry characteristics who have the interest, motivation and ability to complete an engineering degree to do so;
3. To enable students to acquire skills and knowledge essential to the engineering profession;
4. To develop future engineers who are ethical and understand the impact of technology on society and the environment and the need for development that is sustainable.

3 Curriculum design principles

3.1 Broad principles

The brief we were given for the curriculum exemplars was to design curricula that most students would take five years to complete, but that could be completed in four years without losing coherence. The five-year curriculum is considered to be the mainstream, and the four-year curriculum is designated the accelerated programme. Listed below are five overarching design principles that we developed to guide the design of the curriculum exemplars.

1. Consider the pool of engineers, not individual students
South Africa needs to have a pool of engineers with certain skills and knowledge, but the specific knowledge and skills held by each engineer do not need to be identical. On the contrary, there must be some diversity in the skill set and specialised knowledge available within the pool in order to address the need for engineers who are competent to function in different roles. That means that not all engineering students in a particular programme need to take exactly the same courses or follow the same route in order to achieve the expected outcomes.

2. Distinguish between core subjects and options
Core subjects are those that are deemed to be essential for all engineering programmes. To help us identify core subjects, we compared existing programmes of several South African universities and looked for subjects that were part of all (or almost all) programmes in the same area of specialisation. Other subjects are labelled as discretionary (options), but may be required by a particular institution.

3. Allow choice
While certain departments may identify other (non-core) subjects as essential, there should be space within the degree programmes for individual students to pursue their interests. This would result in some students pursuing a programme with greater depth in certain areas, while other students may prefer a programme with greater breadth.

4. Limit students' total load
Students' "total load" should be limited. In the concept of "total load" we include aspects such as the number of assignments, tests and distinct subjects students must deal with simultaneously.

5. Spread out the support for student development
Student development needs to be done over a period of years, not months. Explicit developmental support needs to be provided at *different times* during the programme, not only at the beginning, although more support is needed earlier in the programme than later on.

An interesting feature of an engineering degree is that there are several transition points at which students are expected to be able to think and act in different ways and deal with different types of knowledge (Donald 2002). Most curricula do not make these transitions explicit. We identified the following five distinct transitions students must make during the BEng programme:

1. From high school to university;
2. From basic sciences to engineering sciences;
3. From acquisition of knowledge to design;
4. From knowledge of discrete subjects to analysis of systems and integration of knowledge; and

5. From short, lecturer-led courses to extended student-led projects.

These transitions are challenging for all students, but are especially challenging for students from less privileged home and school backgrounds. We therefore decided that developmental courses were needed, in some cases for all and in other cases for some, students to navigate the transitions. In order to apply the overarching design principles and to help students navigate the five transitions listed above, we propose that the curriculum should consist of four types of courses:

- Core courses for all students,
- Developmental courses for all students,
- Developmental courses for mainstream students, and
- Discretionary courses to be determined by individual departments and students.

The purpose of developmental courses is to help students cope with transitions. A number of aspects of student growth should be explicitly promoted and supported. These aspects could include, for example, behaviours and skills that lead to effective learning, background knowledge, ways of thinking not previously encountered, integration of knowledge and skills and addressing alternative conceptions. The presence of well-designed, well-taught developmental courses in the curriculum should reduce the likelihood that engineering education will fall into the "drift to lower performance" trap. It will also help universities adhere to one of the principles for promoting student success identified by Kuh *et al* (2005, p. 269), namely, "Student success is promoted by setting and holding students to standards that stretch them to perform at high levels, inside and outside the classroom," as more students should be enabled to reach higher levels of achievement.

3.2 Detailed principles

Detailed principles that we believe should underpin the curriculum design are listed below. The word "outcome" referred to the exit level outcomes specified by the Engineering Council of South Africa (ECSA 2004).

- Course credits need to accurately reflect workload (number of hours students are expected to work).
- The design of courses at all levels needs to be based on the characteristics of students for whom they are intended, including their prior knowledge and skills.
- Course level (100, 200, etc.) should be designated appropriately. Level is influenced by, for example, familiarity or novelty of the content, prior content knowledge, skills, mathematical or other proficiencies required, integration or application of more than one prior course required, depth, complexity, conceptual and cognitive demand.
- There is vertical coherence, that is, it is clear which courses must precede or follow others.
- There is horizontal coherence, that is, it is clear which courses can or should be taken concurrently.
- Key transition points need to be identified and supported.
- A variety of skills, including communication and ICT skills, should be developed within the context of specific, identified content courses rather than in separate courses.
- Where possible, courses should be designed so that more than one outcome is achieved.
- Critical pathways should be identified. This includes identifying barriers to progression and providing mechanisms to support progression.
- Cognitively demanding tasks should be spread out across subjects and semesters.

4 Application of the design principles to the exemplars

The exemplars for a four and a five-year curriculum in mechanical engineering are shown in figures 1 and 2. Core courses are coloured green, developmental courses for all but the accelerated programme are yellow, developmental courses for all students are orange and discretionary courses are red. The width of each block corresponds to the credit value of a course. Vertical coherence is indicated by lining up courses under one another. Courses in which writing skills are explicitly developed are indicated with a 'W' after the course code; an 'I' after a course code indicates that ICT skills are developed in that course.

4.1 Total load and credit values

Many students fail in their first year at university because the total load is so much higher than at high school. Students are unprepared for the relatively large volume of work and fast pace at university. To limit the total load in the exemplars there are no more than five courses in each semester. Although the time management skills of students should improve as they progress, taking too many distinct courses simultaneously is a problem for students in all years. There is a temptation in designing engineering curricula to include a large number of "small" (low-credit) courses to cover many topics, but we feel strongly that it is in the students' interests not to do this.

We have allocated most courses 12 credits, where one credit is defined by the South African Qualifications Authority as 10 "notional hours" of study, including formal teaching time, testing and self-study. At levels 200, 300 and 400 we have allocated the design courses 15 credits instead of 12 in order to ensure that the credit value matches the expected time students should spend on these courses.

4.2 Core courses, choice and training a pool of engineers

In the exemplars we identified core courses by looking at a number of different programmes from different institutions. That leaves room for other courses to be added at either a department's or a student's discretion. While some departments will consider certain courses essential for their students, we feel strongly that there should be room for students to be able to choose some of their courses according to their interests. An engineer in a certain discipline needs to have a certain core of knowledge and skills, but within the *pool of engineers* there should be individuals who have specialised knowledge in diverse areas. Therefore some courses that we have labelled "discretionary" should remain unspecified so that students can choose electives, and not only in their final year. Electives could be both technical and non-technical.

4.3 Design courses

Historically, South African mechanical engineering programmes have had a large number of design courses, but these courses have included both subject matter and aspects of the design process. In keeping with international trends, and in the interests of removing barriers to progression, for the mechanical engineering exemplars we have separated out subject matter and design in level 200 and 300 courses into courses named "analysis" in the first semester and "design" in the second semester. Each design course has been allocated 15 credits, while each analysis course has been allocated 12 credits. We suggest that universities allow students who obtained marks slightly below the passing mark in the analysis course at a certain level to repeat the analysis module in the next semester at the same time as they take the design course in order to facilitate student progression.

4.4 Vertical coherence

In the exemplars we have identified several component strands, each of which comprises a sequence of two or more courses. These courses are numbered sequentially and are positioned under one another in the diagram.

4.4 Skills

The development of writing and other communication skills and of ICT skills should be integrated into as many courses as possible. However, in the curriculum exemplars certain courses have been labelled with a 'W', for writing intensive, and/or an 'I' for ICT intensive. In these courses the development of the specified skills will be an explicit component of the syllabus. The three foundation courses in Year 1, Semester 1 of the five-year programme will also help students develop various academic and life skills, such as effective study methods and time management.

4.5 Reducing barriers to progression

Two structural barriers to progression in most programmes are:

- Courses that are prerequisites for other courses,
- Courses that are only offered in one semester.

Some courses require students to acquire specific knowledge and skills in preceding courses. However, there are cases in which exposure to the material in a course, without necessarily passing the course, is sufficient for a student to cope with a later course. In these cases, it may be possible to allow students to repeat the course designated as prerequisite and register for the later course simultaneously. In the mechanical engineering curriculum exemplars, we believe that placing the design courses in the second semester of Years 3 and 4 will aid progression (provided students can repeat the preceding analysis courses concurrently). Options for progression will also be increased if more courses are offered in both semesters. For courses with small enrolments, this would place too much of a burden on academic staff. However, for the larger-enrolment courses, it is likely that offering them in both semesters will not result in a net increase in staff time when compared to offering them once a year to a class that includes a large number of repeaters.

4.6 Developmental courses

In the five-year, mainstream programme, 11 developmental courses have been placed at key points in the curriculum in order to explicitly help students navigate the identified transitions. These courses have been spread out over the whole programme, with a greater concentration in the first semester of the first year. Three of these courses are also part of the curriculum for the accelerated programme.

From high school to university
Mathematics, Physics and Chemistry 101 are foundation courses, and focus on developing understanding of key concepts as well as a range of cognitive and academic skills. Drawing 102 is also a foundation course, designed to help students who have never done technical drawing.

From basic sciences to engineering sciences
Engineering Science 201 is a foundation course for engineering that introduces students to the application of basic sciences to processes and artifacts (components and machines). Engineering Science 301 introduces students to more advanced modeling techniques. Mathematics 202 is a foundation course in mathematics for engineering to help students

develop the facility to link visual, graphical and analytical representations of functions of two variables (surfaces and volumes in three dimensions).

From acquisition of knowledge to design
Design 202 provides an introduction to the identification, selection and analysis of components and artifacts for performing specific functions, as well as the role of estimation.

From knowledge of discrete subjects to analysis of systems and integration of knowledge
Engineering Analysis 302 helps students learn to integrate what they have learned in discrete subjects, such as thermodynamics and mechanics, with mathematics to analyse the functioning of machines and systems, such as engines and heat pumps.

From short, lecturer-led courses to extended student-led projects
Advanced Communication 402 and Project Proposal 401 are designed to help students prepare for the capstone project in the final semester.

5 Conclusion

In this paper we have articulated a number of curriculum design principles and applied them to the design of flexible curricula. Although the curriculum exemplars we devised are for the BEng degree, many of the design principles can be applied to other degree programmes. The massification of higher education necessarily means that students are entering universities with increasingly diverse characteristics. Designing curricula that are flexible yet still coherent, with developmental courses inserted at appropriate points, is a creative solution to increasing student success without falling into system traps.

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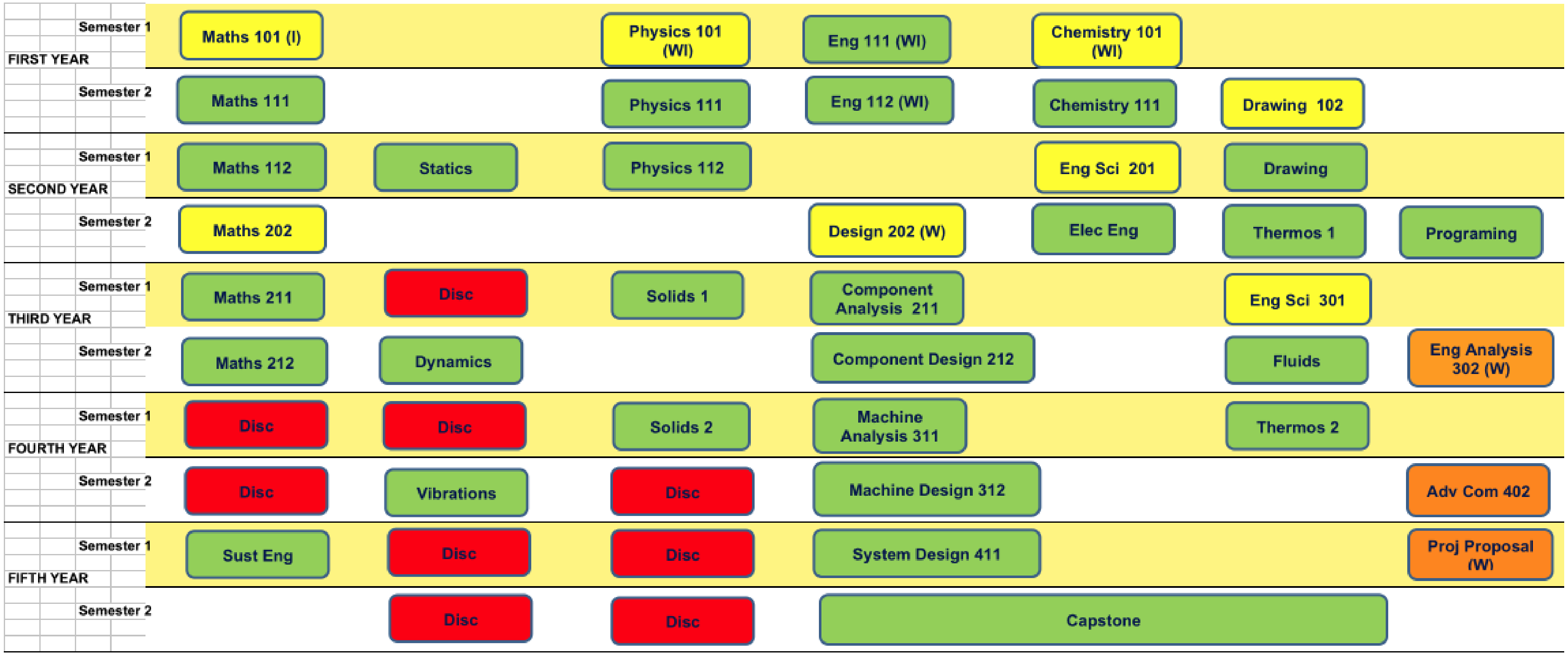
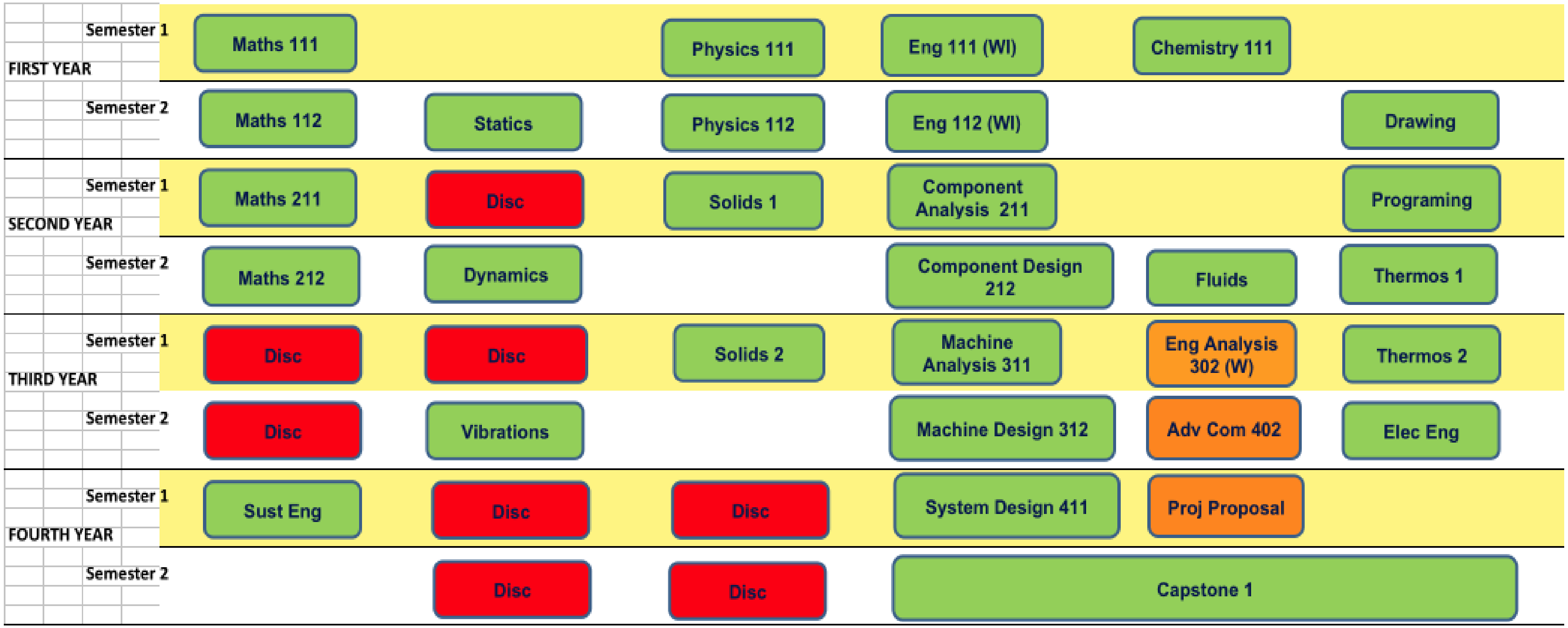
Figure 1: Curriculum exemplar for 5-year (mainstream) Mechanical Engineering Programme



Yellow: developmental (5-year programme)
Green: core
Red: discretionary
Orange: developmental for all students
I: ICT intensive, includes development of ICT skills
W: writing intensive, includes development of writing skills

Figure 2: Curriculum exemplar for 4-year (accelerated) Mechanical Engineering Programme



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