EXTENDED DEGREE PROGRAMME STUDENTS' EXPERIENCES WITH THE SKYSCRAPER ACTIVITY

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ABSTRACT

An activity called "Skyscraper", developed as part of the CDIO initiative (http://www.cdio.org), was implemented with 275 first year students in the Engineering Augmented degree programme (ENGAGE) at the University of Pretoria. ENGAGE is an extended degree programme for students who are not ready to cope with the mainstream programme without support. Implementation of the Skyscraper activity involved logistical challenges as the 275 students were divided into six classes, each of which met for three 50-minute periods in the same week in normal classrooms. All the materials had to be carried from room to room. Within each class, students were divided into groups of about nine people. Students were marked according to six criteria. In a secondary analysis of students' results each group's performance was assessed according to 12 criteria. Problems identified included incomplete project plans, failure to identify constraints or produce a thorough design, not building what was designed, poor time management, failure to perform calculations, incorrect budget calculations, careless mistakes, poor presentation of designs and the need to change the design after building. These problems can be attributed to a variety of sources, including inadequate life skills, poor understanding of basic mathematics, inattention to detail, not understanding the importance of creating and following a design and not transferring knowledge from one context to another. Students who planned poorly may have wanted to get on with what they perceive to be the task—building the structure—arising, perhaps, from their experience of figuring out how gadgets work without reference to systematic analysis or written instructions. For ENGAGE students to gain greater benefit from the Skyscraper activity we may need to devise more structure, such as checkpoints, checklists and budget and materials templates, and create the role of quality assurer in each group. On the positive side, nearly all groups functioned well, especially those that were diverse in terms of race and gender.

KEYWORDS

Skyscraper, extended degree students

INTRODUCTION

South Africa became a constitutional democracy with universal franchise in 1994. Prior to that, the national policy of separate development, or "apartheid", allocated resources differentially according to race and required people of different races to live in separate areas. The highest per capita expenditure was given to Whites, then Indians, then people of mixed race, with the lowest expenditure being allocated to the majority population comprising indigenous Africans. The effects of this policy are still being felt 17 years after the end of apartheid in health, housing, infrastructure and education. Science, technology, engineering and mathematics (STEM) education are a priority for the government [1], as there can be no development without adequate skills in these fields. While improving the quality of education, especially STEM education, needs to begin in primary school, South Africa cannot afford to wait a generation for the school system to improve before it takes steps to increase the number of STEM professionals produced by universities.

Universities therefore embarked on various academic development initiatives, pioneered by a small number of universities more than 20 years ago. By 2001 most universities had some sort of special programme [2] in science and/or engineering for students from historically disadvantaged backgrounds. These programmes were typically "add-on", meaning that additional courses and other forms of support were provided that did not count towards the degree. Furthermore, while the programmes were usually exemplary in terms of curricula and teaching methods, they were often taught by junior staff and had little impact on mainstream academics or courses.

A longitudinal study of the cohort of students that entered all South African contact universities in 2000 [3] showed that only 38% had obtained a bachelors degree after five years. (The regulation time is three years for a general bachelors and four years for a professional bachelors degree, such as engineering.) In engineering this figure was 54%, with a large difference in graduation rates for White and African students, 64% and 32%, respectively. It was clear that many students could benefit from academic development and support.

In 2006 the Minister of Education declared that all academic development programmes had to be mainstreamed. That meant incorporating them into credit-bearing, extended degree programmes with a coherent curriculum and opening them up to all races. At the University of Pretoria, a five-year programme in engineering had been in existence since 1994 in which the first two years of coursework had been distributed over three years, with extra tutorials offered in some first-year courses. However, statistics compiled for the 2002 cohort of students in that programme showed that after seven years only 54% of students had graduated. Of the African students only 35% had graduated [4].

A new problem arose in 2009 when the first group of students who wrote the new national school leaving examinations based on a new curriculum performed very poorly in their first year university STEM courses around the country. Anecdotal evidence suggested that these students' knowledge of basic facts, ability to solve problems and experience with working hard were less than those of previous cohorts of students. A study at the University of the Witwatersrand showed that student performance in mathematically-based courses decreased significantly [5]. Thus in 2009 a new 5-year extended degree programme for engineering was designed, the Engineering Augmented Degree Programme (ENGAGE).

STRUCTURE OF THE EXTENDED DEGREE PROGRAMME

The design of the Engineering Augmented Degree Programme (ENGAGE) was informed by the first author's experience in developing the Science Foundation Programme at the then University of Natal in the early 1990s [6,7]. In designing that programme, cognisance was taken of Vygostsky's notion of the need for enculturation (in that case to the university) [8] and to provide "good instruction," about which Vygotsky (quoted in Wertsch and Stone [9]) says,

> "instruction is good only when it proceeds ahead of development, when it awakens and rouses to life those functions that are in the process of maturing or in the zone of proximal development."

The implication of this statement for an academic development programme is that as students develop the demands of the programme need to increase.

The design features of the ENGAGE programme were articulated as follows:

1. Students should be supported in making the transition from high school to university.
2. Student workload (time students spend working) should be high throughout.
3. The volume of work (amount of content covered) should be low initially and increase over time.
4. Support should be high initially and decrease over time.
5. Students should encounter familiar subjects early in the program, less familiar subjects later on.

These principles are applied in practice in the following ways [10]:

1. All 16-credit (one credit represents 10 hours of notional study) level 100 modules are augmented by an additional 8-credit module.
2. In Year 1 students take a reduced load comprising only level 100 basic sciences modules and additional modules, together with two semesters of the skills-based course Professional Orientation.
3. In Year 2 students take level 100 engineering modules and additional modules plus half of the level 200 mathematics.
4. In Year 3 students take level 200 engineering modules and the rest of the level 200 mathematics. The credit load is only slightly lower than for mainstream students in Year 2.
5. In Years 4 and 5 students join the mainstream for level 300 and 400 modules.

Professional Orientation and the additional modules are developmental in that their focus is on developing a range of cognitive, metacognitive, academic and communication skills as well as conceptual understanding. Table 1 provides a comparison between the ENGAGE curriculum and the mainstream 4-year degree programme.

Table 1
Comparison of the Structure of the ENGAGE and 4-Year BEng Programmes

ENGAGE		**4-Year Programme**	
YEAR 1	credits	YEAR 1	credits
Mainstream Science (level 100)	64	Mainstream Science and Eng (level 100)	144
Developmental	48		
YEAR 2			
Mainstream (level 100 + one 200)	96	Mainstream (level 200)	144
Developmental	32		
YEAR 3			
Mainstream (level 200)	128	Mainstream (level 300)	144
YEAR 4			
Mainstream (level 300)	144	Mainstream (level 400)	152/160
YEAR 5			
Mainstream (level 400)	152/160		

Since ENGAGE students take no engineering modules in year 1, they have little exposure to engineering except for some of the projects in Professional Orientation and reading *Engineering News*, a weekly South African magazine. It therefore seemed very appropriate to provide them with an opportunity to do the Skyscraper activity that was developed as part of the international CDIO initiative. According to the CDIO website (http://www.cdio.org),

> "The CDIO™ initiative is an innovative educational framework for producing the next generation of engineers. The framework provides students with an education stressing engineering fundamentals set in the context of Conceiving — Designing — Implementing — Operating real-world systems and products."

PREPARING TO RUN THE SKYSCRAPER EXERCISE

In the level 100 Physics module students cover Newtonian mechanics, including centre of mass calculations. Since this is the only background knowledge required for the Skyscraper exercise, we decided to do the exercise in the Additional Physics module soon after centre of mass had been covered.

The Skyscraper activity has been developed over time by members of the CDIO initiative. A detailed document, Skyscraper Template, by Dan Frey and Ed Crawley from MIT, can be downloaded from the CDIO website. According to the document, the overall goal of the activity is to, "Allow students to describe, anticipate and plan for some of the realistic factors encountered in a real engineering project through a team activity." In the activity students follow the CDIO process and work in teams to design and build a "skyscraper"—as tall a building as possible—out of polystyrene and pencils with a limited budget. The building needs to have structural integrity and be able to withstand an "earthquake", operationally defined as not tipping over when a half litre bottle of water is placed on top and the structure is tilted so the slope is 1 in 10.

The first author participated in the Skyscraper workshop at the 2010 CDIO conference, while the other authors participated in a workshop run by David Wisler during a visit to the University of Pretoria in October 2010. Thus we all had first-hand experience of the activity. In both cases, participants spent about three hours on the activity all in one session.

In the ENGAGE programme we had 275 students that were divided into six classes. Each class met for one lecture and three 50-minute discussion periods per week. The discussion periods are staffed by one lecturer and one student tutor per class. The activity was run during the discussion periods. Students did the conceive phase during the first period, the design phase in the second period and the implement (build) phase in the third period. The activity was carried out with all six classes in the same week, involving a total of 18 teaching periods. It was lead by the third author, who was the course instructor, with assistance from the second author and one student tutor per group.

The discussion periods took place in normal classrooms around the campus with moveable tables and chairs, so all materials had to be carried into these rooms. Space is a problem at the University of Pretoria, with its approximately 40 000 students. Limited space meant that only about five groups could work in a room at one time, resulting in group sizes of about 9 members, which is probably too big. There were a total of 32 groups.

An unforeseen problem we encountered was trying to source the extruded polystyrene foam that is one of the two building materials specified in the Skyscraper template. Most of the polystyrene available in South Africa is expanded, not extruded, which is too friable. Numerous inquiries had to be made before a company was found that sold extruded polystyrene. In future it may be possible to find a suitable local alternative, but it will be a challenge to match the strength, rigidity, cost and low density (which enables the creation of fairly tall structures) of the extruded polystyrene.

RESULTS

Student groups were marked out of 100 according to the marking scheme shown in Table 2. No peer marking was done because of time and staffing constraints.

Table 2
Marking Scheme Used for Skyscraper Activity

Feature	Marks	Feature	Marks
Stability	30	Aesthetics	5
Height	20	Time and organisation	10
Budget	5	Documentation	30

The two criteria on which the largest number of groups lost marks were budget and documentation. Of the 32 groups only 5 scored at least 3/5 for budget. This is probably reflective of a general problem in South Africa that many adults, let alone beginning university students, have very poor personal financial management skills. (Since the global recession there has been a proliferation of debt counsellors.) For the criterion of documentation associated with their design only 5 groups scored at least 25/30, while 9 groups scored 20/30 or less. It seems that many of the students lacked planning skills and were eager to just get on with the building.

We carried out a secondary analysis of the students' performance to identify more clearly where they had problems. The criteria we used for this analysis were:

1. Complete project plans
2. Conceiving constraints
3. Thorough design
4. Following documentation ("gap" between as designed and as built)
5. Time management
6. Evidence of effective group work (backed up by photographs)
7. Focus on aesthetics above functionality
8. Calculations based on physics principles
9. Correct budget calculations and materials list
10. Attention to detail in calculations and materials list (no careless mistakes)
11. Quality of design presentation in drawings and/or words
12. Changes made to design during or after building to meet requirements

Each group's performance was analysed on a scale of 1 (low) to 3 (high) for each criterion. The results are summarised in Table 3.

Table 3
Percentage of groups scoring 1, 2 or 3 for each criterion used for secondary analysis

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
1	16	41	16	16	13	9	78	63	38	3	16	47
2	34	28	22	25	38	0	13	6	22	75	25	28
3	50	31	63	59	50	91	9	31	41	22	59	25

The following problems with the groups' performance are evident from Table 3:

- Only half produced a good project plan;
- Less than one third thought through the constraints carefully in the conceive phase;
- More than a third did not produce a thorough design;
- More than a third deviated from their design when they built their structure;
- Only half managed their time well;

- 9% focused more on aesthetics than functionality
- Less than one third did calculations of underlying physics needed for the design;
- Less than half did correct budget calculations and produced complete materials lists;
- Less than one quarter made no careless mistakes in calculations;
- More than one third did not present their designs well;
- More than half of the designed structures did not meet the requirements and had to be adapted.

Informal observations suggest that poor performance on criteria 1 and 2 seemed to be attitudinal. Students did not appear to want to take time for careful planning, eager instead to get on with the building. In some groups too much time was spent discussing the task and allocating roles so they then had to rush. The gap between what was designed and what was built by a number of groups suggests a lack of attention (to the design) and intention (understanding the importance of doing the design). The fact that so few students provided correct calculations of the centre of mass (criterion 8) was surprising given that they had just covered the topic in physics. This could be a manifestation of the well-documented problem of lack of transfer between the domain in which a concept in learned and a different context in which it needs to be applied [11]. Poor performance in criteria 9 and 10 points to lack of care, possibly at least partially as a result of hurrying the task too much. Some errors arose from poor understanding of basic mathematics, errors that should have been detected if group members had checked each others' work. For criterion 11, one of the reasons that many of the designs were not well-presented is that ENGAGE students only take engineering drawing in year 2 and a number of our students arrive from high school with no drawing expertise, even at a rudimentary level.

Figure 1. A heterogeneous student group with their "Skyscraper"

On the positive side, nearly all of the groups functioned well. At high school students are used to having to work in groups. South Africa is a multi-ethnic, multi-cultural society. Interestingly, informal observations suggest that teams comprising students from different backgrounds functioned more effectively than homogenous groups. Delegating tasks among all group members also led to better group functioning.

On a questionnaire at the end of the Physics module, students responded to the statement, “The Skyscraper exercise increased my understanding of how engineers think and work.” On a 4-point scale, 78% of students answered “a lot” (1) or “some” (2).

CONCLUSION

The Skyscraper activity provides a very nice introduction to beginning engineering students of the variety of factors that need to be taken into account in an engineering project, including technical, budget, time and team. It exemplifies the CDIO approach to engineering education. For the first year ENGAGE students, who have not yet begun their engineering courses, it enabled them to get a feel for what an engineering project entails, as well as providing an opportunity to apply their physics knowledge and to work in teams.

Two types of difficulties arose, one relating to the organisation of the activity and the other to the students’ performance. We found it very challenging to implement the activity with so many students and so few staff in classrooms all over the campus, which involved carrying the materials from place to place from one period to the next. Ideally, it would be better to secure a single venue for this activity. A new engineering building is nearing completion, so this may be possible in future. The small number of instructors also made it difficult to carefully monitor whether students were meeting all the requirements, such as producing correct materials lists and project plans.

The secondary analysis of difficulties displayed by the groups points to a lack of a variety of skills, some of which could be considered general life skills, such as time management and avoiding careless mistakes. Others are related to dispositions, such as wanting to do what students perceive to be the task (creating the structure) without proper planning. Perhaps this is a sign of the times, where young people routinely figure out how gadgets work by trial and error, without having to read instructions or follow any systematic process. Some of the difficulties are related to skills, such as poor drawings. Given the difficulties students displayed, we need to provide ENGAGE students with more structure and support during the Skyscraper activity. To this end, we have designed an additional handout that clearly spells out what students need to do in each period and lists roles for team members in addition to those in the Skyscraper handouts, such as Quality Assurer, Time Keeper, Record Keeper and Financial Manager (see Appendix). Some people may feel that we have provided too much information, but given the developmental needs of our students we think they will get more out of the activity if they are given more structure.

In the Professional Development module in the second semester of Year 1 we provide students with another opportunity to participate in a CDIO activity. The task is to build a crane from Lego components that meets certain specified requirements. Students first work on the internet on their own to learn about gears and levers, then form teams to conceive, design, build and operate their cranes.

We have identified two second-year ENGAGE modules, namely, Graphical Communication and Mechanics (statics), in which we intend to further develop the concepts involved in the Skyscraper activity. For example, in the existing activity students assume that the centre of mass for their structures coincides with the centre of mass of the water bottle. For most designs, this yields a maximum height that is lower than the actual possible height. In

Mechanics we will show students how to consider the effects of the mass of the pencils and polystyrene on the position of the centre of mass.

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APPENDIX: Additional student handout for the Skyscraper activity

Skyscraper Project

Starting from the week of the 16th of May, we will be embarking on a project to build skyscrapers to demonstrate CDIO principles. This documentation gives information to students about the project as well as the assessment criteria that they will be marked on.

Students have been grouped into groups of 4 to 8 members. Each group must choose three team leaders:

1. Overall Project Engineer
2. Design Leader
3. Implementation Leader

Additional roles that need to be filled by other group members are Quality Assurer, Time Keeper, Record Keeper and Financial Manager. More than one student may fulfil each of these roles.

Each group must choose a team name, and assign roles within the group by the end of their last Discussion Class of the week of the 9th of May.

The project will be marked out of a 100. Seventy five (75) marks will be assigned to the group based on their documentation and their skyscraper, 20 marks will be assigned to each group member by other group members, and 5 marks will be assigned for the completion of a reflection questionnaire.

Below is a schedule to help student to know what needs to be handed in at what stage of the project:

1. By the end of the first session, each group should have submitted the Conceive section of their documentation. This involves defining customer needs, and then developing conceptual, technical and business plans to meet those needs, while considering the technology and materials at your disposal, as well as regulations that apply. **(NO DESIGNS MAY BE DRAWN UP IN THIS SESSION)**

2. By the end of the second session each group should have submitted all the Design documents. This includes:
   (i) Detailed drawing and sketches
   (ii) A structural analysis
   (iii) Detailed manufacturing instruction
   (iv) A construction plan
   (v) A budget

   Students must obtain a building permit by the end of this session in order to proceed with construction in session three. All the above documentation is required to obtain such a building permit.

3. By the end of session three the building must have been constructed and tested.