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AN OUTCOMES BASED FIRST YEAR ENGINEERING DESIGN SYLLABUS AIMED AT WELL PREPARED AND DISADVANTAGED STUDENTS

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Abstract

Engineering design education in developing countries not only has to cater for vastly unequally prepared learners, but should also equip learners with skills that will ensure their international competitiveness. Teaching engineering design on the freshman level is faced with another challenge, i.e. the (as then) lack of exposure to the engineering sciences. In the present study the author adapted a freshman course in engineering design essentially to include basic design by experiment as a competitive design tool and to structure the syllabus content according to specific assessable outcomes. The previous course structure of core lectures, ten practical and two design projects was retained but the contents of the lecturing component and the second design project were changed mainly to accommodate design by experiment. It was found that learners considerably expand their engineering knowledge by conducting the practical project course component and that it is indeed possible for the average freshman to master basic design by experiment techniques adequately. It also appears as if the performance of previously disadvantaged students is improved by following an outcomes based approach.

Keywords: Engineering design education

1. Introduction

The wide variation in level of preparedness of first time entering students is one of the challenges facing tertiary education institutions in Southern Africa. Students from high schools of varying educational standard enter universities and attend the same lectures. Some of these students are the products of up-market private and public schools but many others attended high schools with limited resources. Colloquially the latter class of student is referred to as a *previously disadvantaged individual* (pdi). Typically, about half the first year engineering intake falls in the disadvantaged category. Educators have to guide the learning process such that the poorly prepared can cope, but at the same time, the rest is not bored, and internationally accepted standards are maintained.

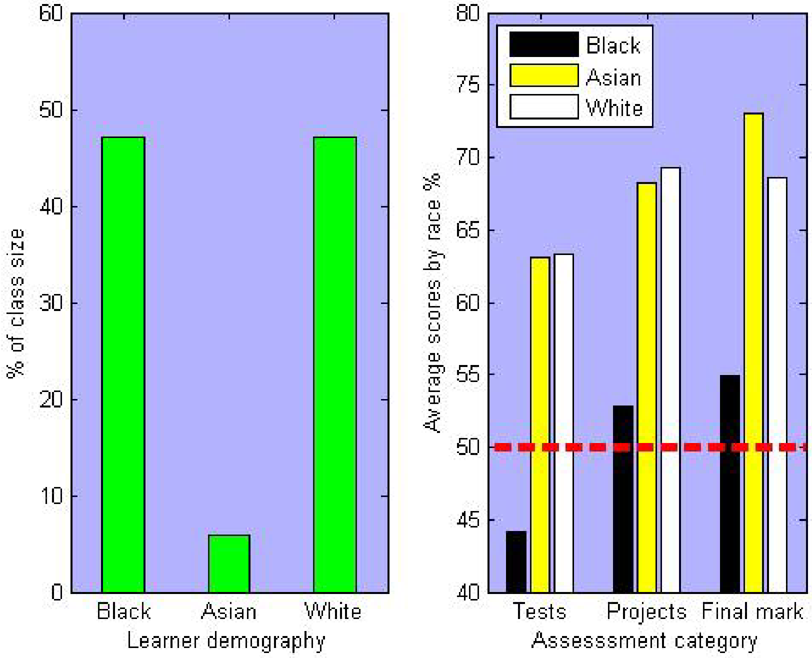

Figure 1. Learner performance in third year design course MECN371 for 2004

That the disadvantaged often struggle academically at university, is well known. As will be suggested later, racial classification could be seen as a crude indicator of historic privilege in South Africa. The general impression amongst local faculty in mechanical engineering education is that (on average) black students, likely to have been previously disadvantaged, struggle more with their studies than their white counterparts. Figure 1 highlights this typical phenomenon for a third year course in mechanical design. Considering the pass requirement of 50%, it is clear that the average pdi couldn't pass the class tests, hardly passed the design projects and only obtained an acceptable final mark due to the inclusion of a "soft" course component. To further complicate matters, research conducted by Meyer and Sass [1] revealed that remedies for *academically at risk* learners can not effectively be administered on a group basis. Individual students require fundamentally different forms of educational intervention.

Contemporary designers can not escape from the competitive pressures associated with earning a living in the global village. The incompetent or poorly equipped do not survive. It is the responsibility of the education establishment to equip students of engineering design with best practice skills that will give them a winning edge. Exactly what these necessary skills are, is context dependent and not always clear. An international standard benchmark for an engineering design curriculum does not exist. Useful pedagogic guidelines based on design science have been provided by Hubka and Eder [2], and a high level design curriculum is proposed by Eder and Hubka [3]. But, on the detail level, the need to introduce specific topics such as axiomatic design, robust design or TRIZ is left to the judgment of practicing educators.

Educators also face another difficulty: the lack of exposure to engineering hardware by most students entering university. This phenomenon could be due to a) the huge amount of time that the young generation spends on computers from an early age and b) the absence of technological artifacts in the living environments of the disadvantaged.

When it comes to teaching engineering design on the freshman level, a further problem presents itself. Learners have had no (or very little) exposure to the engineering sciences, complicating the teaching of domain specific methodologies such as the design of machine assemblies or control circuits.

In summary, at least five categories of challenges are to be addressed when attempting to teach engineering design to freshmen in a typical, contemporary, developing country: The dissimilar preparedness of learners, pdi's struggling with their studies, individual learner remedial requirements, the responsibility of having to achieve competitive outcomes, and learner ignorance regarding both the engineering sciences and engineering devices.

In the present paper an attempt at adapting a freshman syllabus in engineering design, to address some of these difficulties, is described. The course, entitled MECN124 *Introduction to Mechanical Engineering and Design*, had been offered for a number of years, by various lecturers. It had consisted of four components

1. A core component consisting of lectures.
2. Ten practical projects.
3. Two design projects.
4. A test and an exam.

The core component had included a variety of topics such as introduction to the design process, generation of a PRS (Product Requirement Specification), report writing, materials, manufacturing, modelling and fits and tolerances. The ten practical projects were intended to expose learners to existing technical systems with regard to their function, their construction and rudimentary performance calculations. Examples of these technical systems are a trolley jack, an electronic amplifier (Figure 2), a garage door, an internal combustion engine, a motorcycle gearbox, a Mirage aircraft and an electric drill. Two design projects were undertaken. The first, a paper exercise, concentrated on task clarification, conceptual design and the generation of a PRS. The second was devoted to the detail design, construction and testing of a simple device. Partly due to the large class size, all projects were done by students working in groups. The course was run on a semester basis with four 45 minute lectures and one afternoon session per week.

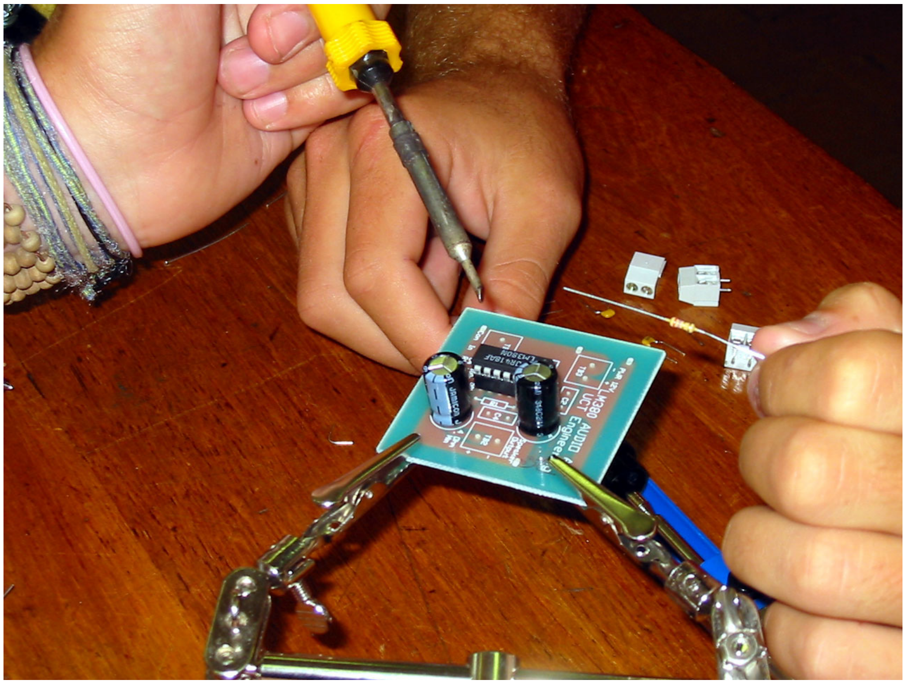

Figure 2. Learners building an electronic amplifier

The prior course presentations could be considered on all accounts to have been successful. However, the opportunity to add educational value occurred soon to the author when first assigned to the course. Although the core component covered valuable material, the various topics did not coherently constitute a whole. The core material also did not fully occupy the available lectures. The "vacant" lectures were used to view technical video films which, of course does have educational benefit. The second design project, where students had to design, build and test a device, was intended to expose students to mechanical design, team work, creativity, sketching and drawing, exposure to mechanical workshop practice and report writing. These objectives were largely met but it seemed that even more educational benefit could be reaped if this project was slanted towards a *design by experiment* approach. As used here, design by experiment refers to the experimental optimization of a product using design of experiments (DOE) and Taguchi's robust design philosophy. Design by experiment is closely related to *robust design methodology* (RDM) as discussed in Arvidsson et al. [4]. To some extent, design by experiment allows design optimization without having to resort to a theoretical model describing the device's behaviour. This is attractive on the freshman level due to the typical learner's limited knowledge of engineering science and their limited ability to model system behaviour. In fact, as theoretical models attempting to model system behaviour often suffer from lack of realism, design by experiment should perhaps in future receive more emphasis in design engineering curricula beyond the first year. Design by experiment is considered a powerful, generic design technique that could contribute towards design competitiveness.

Efforts to adapt the course to include design by experiment as a major component, whilst attempting to address the challenges mentioned earler, are described below. The author had the opportunity to present the course twice in succession at the University of the Witwatersrand, Johannesburg. The class typically consisted of about 200 learners.

2. Chosen approach

As discussed above, including design by experiment was the major innovation introduced to the course. To be able to apply this methodology, a number of distinct knowledge areas are to be mastered (columns one and two, Table 1). Reference 5 gives a succinct description of RDM whilst references 6 and 7 contain excellent introductions to the subject. At a first glance, the apparent complexity of some of these knowledge areas precludes their treatment in the freshman year. However, limiting the intended educational outcome to basic skills levels, it is sufficient to focus only on introductory concepts and techniques belonging to the various knowledge areas.

When applying RDM in industry, engineers use a number of methodologies other than those listed in Table 1. Examples of those not addresses in this paper are [4]: statistical process control, simulation techniques, process failure mode and effects analysis, capability measures, design for manufacture/assembly and fault tree analysis. That these techniques contribute towards effective application of RDM is accepted but attempting to introduce freshmen to the basics of RDM within the constraints of course size and learner background, precludes coverage of all these related topics.

For the current investigation, basic skills levels in the various knowledge areas are defined in the third column of Table 1. At this skills level, under the supervision and guidance of someone more knowledgeable, a learner should be capable of planning and conducting an experimental programme, analyzing the data and predicting an optimum design configuration for relatively simple cases. In particular, the learner should be capable of:

- Manipulating statistical data into histograms and calculating averages, standard deviations and coefficients of variation.
- Fitting a zero-point-proportional straight line to a set of measurements in the least squares sense.
- Describing a device by means of a Phadke diagram in terms of a quality characteristic, noise factors and control factors.
- Selecting quality and control factors to promote additivity of control factor effects.
- Working with signal-to-noise (S/N) ratios.
- Using a given orthogonal array to define required control factor level combinations for each experimental run.
- Conducting the experiments and recording the measurements.
- Analyzing the data to extract the various factor effects using analysis of means (ANOM).
- Using a predictive equation to predict the optimum design configuration.
- Performing a verification test and judging whether control factor additivity had been achieved.

Table 1. Required knowledge areas for design by experiment

Knowledge area	Sub knowledge area	Basic skill level
Statistics	Stochastic variables	Identify discrete and continuous stochastic variables; analyze samples and populations
	Distributions and their properties	Construct histograms; calculate means, standard deviations and coefficients of variation
	Regression	Perform a least square fit to the zero-point proportional case
Design of experiments	Running experiments using orthogonal arrays	Allocate control factor levels; assign control factors to columns; define each experimental run including scale and noise factor influences
	Orthogonal array selection	None, except for ensuring that the required control factor experimental degrees of freedom (DOF) do not exceed the available experimental DOF
	Orthogonal array modification	None
	ANOM: extraction of factor effects	Apply standard ANOM and portray the results on composite graphs; search for a scaling factor
	ANOVA: factor significance and error	None
	Experimental efficiency	Calculate experimental efficiency if given a particular orthogonal array and control factors and their levels
Design by experiment	Quality, noise and robustness	Define product quality according to the philosophies of Taguchi and Juran; identify various categories of noise factors; define robustness
	The Phadke diagram	Describe a product schematically as a black box with inputs (noise, control and scaling factors) and outputs (quality characteristics)
	Quality characteristic selection for additivity	Classify quality characteristics and apply established guidelines for choosing them
	Control factor selection for additivity	Apply established guidelines for identifying control factors; compound control factors and use sliding levels
	Signal-to-noise ratio and its selection	Calculate the S/N ratio (selecting the S/N ratio is excluded)
	Noise experiments	Accommodate various noise influences in the experimental matrix
	Prediction of optimum configuration	Identify optimum control factor settings from control factor plots; predict the performance of the optimum using linear equations
	Verification and interpretation	Perform verification experiments and decide whether the additive assumption is valid

The capability to select quality characteristics and noise and control factors to achieve additivity of control factor effects, is a difficult skill to master. Insight into the physical mechanisms of “energy transfer” taking place in the system is normally required. Although the lack of knowledge regarding the engineering sciences could be problematic here, it was hoped that learner attempts at defining quality characteristics and noise and control factors would foster the ability to qualitatively analyze a system’s physical operation and anticipate relationships between design parameters.

Skills and knowledge related to design by experiment that would **not** be included in the syllabus, are:

- Taguchi’s quality loss functions.
- Selecting appropriate orthogonal arrays.
- Construction and modification of orthogonal arrays.
- Working with interactions between control factors.
- Using Taguchi’s linear graphs to assign interactions to columns of an orthogonal array.
- Performing analysis of variance (ANOVA) to estimate error variance and for determining the relative importance of various factors.
- Selecting appropriate S/N ratios.
- Curve fitting multi-parameter *phenomonological equations* [8] to experimental data.
- Applying the related methodologies listed by Arvidsson [4] and summarized in the second paragraph of this section.

Other topics (besides design by experiment) were also included in the course syllabus. These are:

- An introduction to technical systems: Examples of technical systems such as the International Space Station, structures, mechanisms and machines, engines and heat pumps; hierarchy of component structures, functional descriptions; product functions, characteristics and properties; product and portfolio architecture [8]; the general transformation process [9]; technical system evolution and life cycles (4 lectures).
- The design process: The basic design cycle of Roozenburg and Eekels [10]; the structured design process [11]; generation of a PRS; functional analysis and morphological matrices; brainstorming; generation of solution concepts; simulating product behaviour (4 lectures and 2 design projects))
- Report writing (1 lecture and 2 design projects).
- Introductory detail design and manufacturing: Support structures and assemblies; machine elements and their functions; engineering materials; manufacturing processes (12 lectures).

In the year 2004 learners completed two design projects, working in groups. Design project 1 was a paper exercise in which a mechanical torque limiter had to be designed. The emphasis was placed on Task Clarification, Conceptual Design, rudimentary modelling, PRS generation, sketching and report writing. Design project 2 was an exercise in designing, building and optimizing a water clock. The water clock concept, which is based on an ancient Chinese design, lends itself superbly to application of robust design (Figure 3 [12]).

Figure 3. A water clock project, as seen by National Geographic [12]

3. Course assessment

A number of staff members and graduate students were assigned to the course to assist with the conduction of the practical projects. These individuals also marked the short tests and reports related to these projects.

As far as the core course material was concerned, a single class test, an exam and the design projects served to assess whether course outcomes had been achieved. Course topics dealing with manufacturing were presented by another lecturer. As the author was given little additional assistance with regard to the running of most core course components and the class size was large, assessment mechanisms had to be carefully structured so as to avoid unmanageable workloads.

To limit the marking effort, it was decided to set the test and exam questions such that a fairly large number of short questions are posed and their solutions are independent of each other. In addition, learners had to transfer their final answers to specially formatted answer sheets which were the only documentation to be marked. This approach made it possible to mark the entire exam within a day's work.

4. Results

Results obtained for the course as presented during the academic year 2004, will be analyzed in this section.

4.1. Class demographics

In order to assess the differences between learning success for disadvantaged and traditional students, one of course has to be able to classify each learner accordingly. This is difficult, as it is dangerous to equate race, which is easily determined, to standard of prior education (e.g. blacks and whites were educated poorly and thoroughly, respectively). Thanks to aggressive national transformation policies, for example, a number of black school learners are currently supported to attend prestigious private schools. Surely these cases are not to be seen as having been disadvantaged. But, lacking better background information and seeing that the University does record this type of information, learners will be categorized according to race here. It is probably "not too incorrect" to say that, despite the huge investment in transformation in South Africa, black students are today still disadvantaged with respect to their white counterparts, in general.

In the year 2004 a total of 188 learners wrote the final exam in MECN124. The racial and gender mix of this group is as shown in Figure 4. No racial information was available for some learners, here classified as *uncertain.* Acronyms used area BM = black male, BF = black female, AM = Asian male, AF = Asian female, WM = white male, WF = white female, U = uncertain. Due to their small numbers, the three female groupings are statistically not very significant and conclusions drawn regarding gender effects should thus be treated with caution.

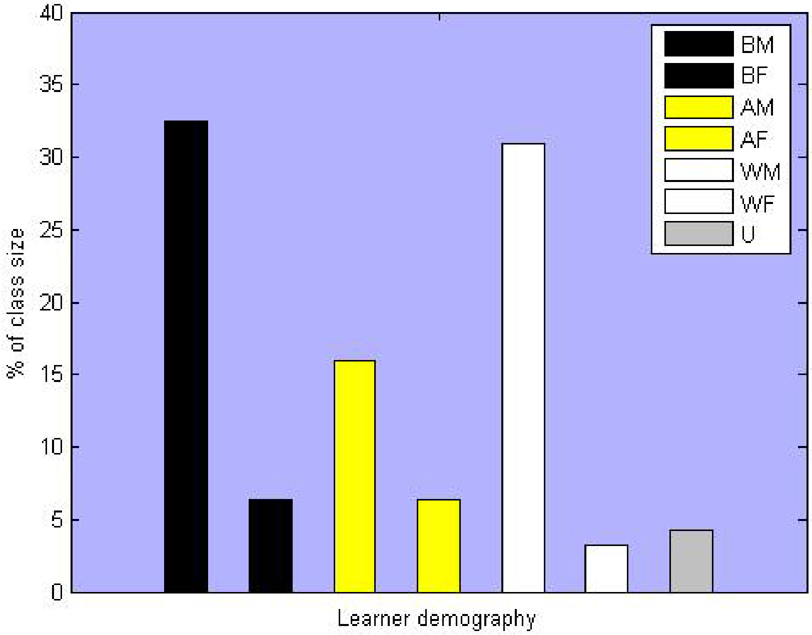

Figure 4. Racial and gender composition of MECN124 in the 2004 academic year.

4.2. Results of course assessment

The results for major course assessments are shown in Figures 5 and 6. These assessments are design project 1, design project 2, the ten practical projects, the class test, the exam and the final mark, which is a conglomeration of the other marks. Figures 5 and 6 show average marks and representation of the various groups amongst the top scorers, respectively.

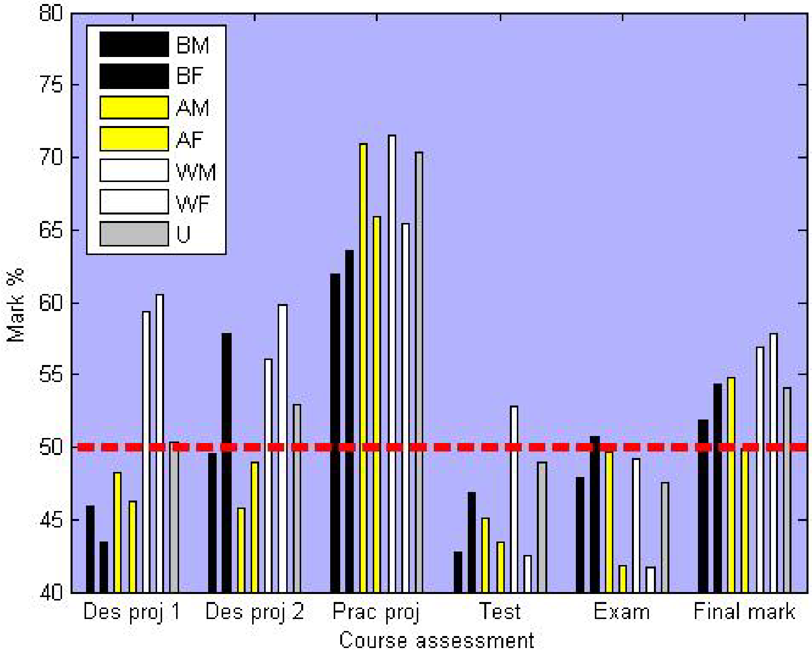

Figure 5. Results of course assessment for MECN124 in the year 2004 (average marks shown)

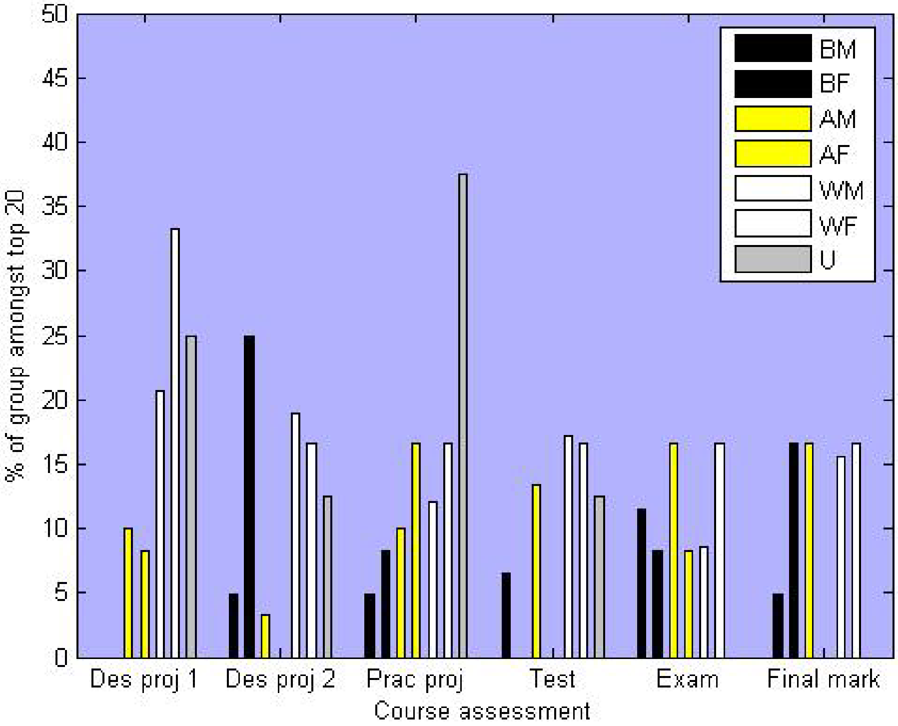

Figure 6. Results of course assessment for MECN124 in the year 2004 (top performers)

The results for lower level course assessment, based on assessing some outcomes, are shown in Figure 6.

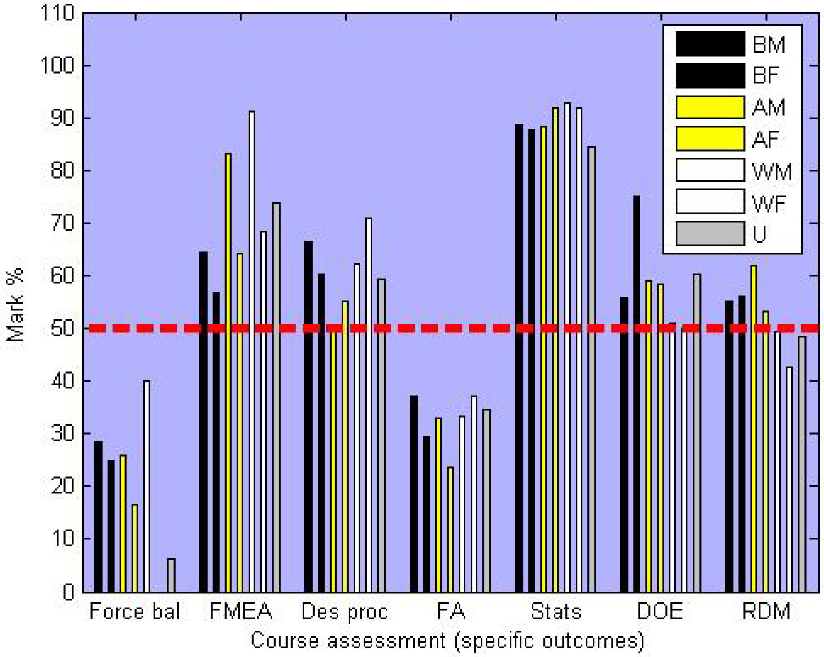

Figure 7. Course assessment with regard to specific outcomes (average marks shown)

Acronyms for the various outcomes depicted in Figure 7 are: Force bal = identifying and balancing forces acting on an object in equilibrium, FMEA = failure mode analysis for a simple engineering operation, Des proc = application of the structured design process, FA = application of functional analysis, Stats = basic statistical calculations, DOE = using and interpreting orthogonal arrays and RDM = application of the robust design method.

Figures 5 and 7 only show average scores. A large spread in results was often observed. Considering the top end of the final mark scale, amongst the top 20 performers (Figure 6), two students top scored with 84%. In this group we had BM = 3, BF = 2, IM = 5, IF = 0, WM =9, WF = 1 and U =0. About 6% of all students didn't manage to obtain 40%, implying that they would probable not be allowed to write the supplementary exam and hence fail the course (permission to write the supplementary exam also depends on scores in other courses). Figure 8 shows a composite histogram of the final marks for the three race groups.

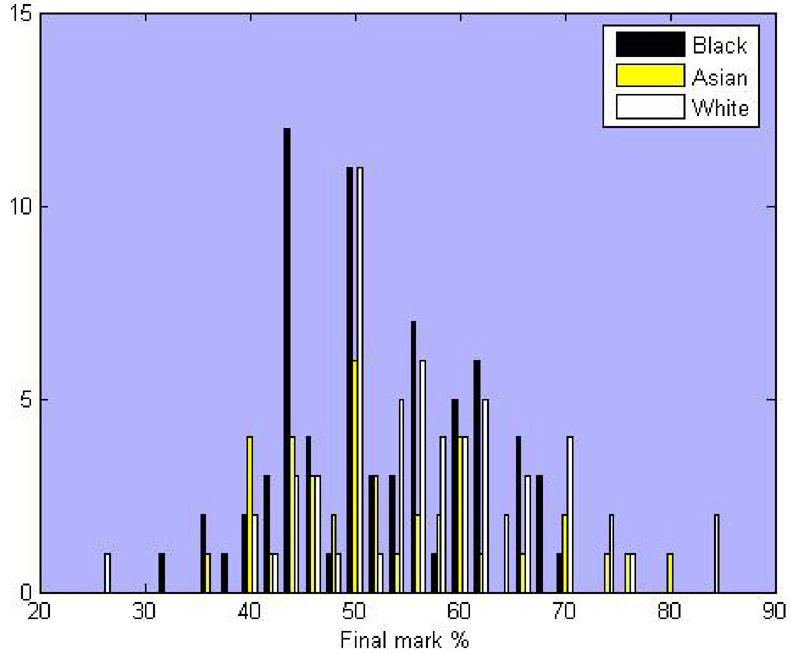

Figure 8. Composite histogram of final marks for MECN124 in the 2004 academic year

5. Discussion of results

Referring to the grouping of final marks shown in Figure 5, it was disappointing that the average student barely passed the course (a score of 50% is required). Studying the scores of the various assessments in the same figure, it is obvious that the scores for the practical projects are the highest. This is probably because this course component is (a) popular with learners and (b) the projects aren't particularly difficult to complete.

Returning to Figure 5, it is clear that design project 1, the class test and the exam presented the biggest obstacles. The distributions within the various groupings are interesting. Differences in black and white learner scores for the final mark, the exam and design project 2 appear more subdued than for design project 1. In fact, the average black student actually slightly outperformed his white counterpart in the exam.

Design projects 1 and 2 were conducted in the first half and the second half of the course, respectively. When one compares corresponding results for these projects in Figures 5 and 6, it appears that black learners had improved substantially over the course duration. The same conclusion is arrived at when one compares corresponding test and exam scores in the same two figures (the format of the questions in the test and exam was quite similar). Possible explanations could be:

1. Black learners initially struggled to adapt to the course environment and its expectations but then developed rapidly and caught up.
2. Black learners initially struggled to adapt to the course environment and its expectations, under performed and hence received a "wake up call". Consequently they worked much harder than white learners did in design project 2 and in preparation for the exam.

3. Black learners initially struggled to adapt to the course environment and its expectations, but as the course progressed and became more outcomes based (e.g. design project 2 was particularly based on outcomes), they managed to cope. The difference in results for design projects 1 and 2 was probably due to their vastly different nature. As mentioned earlier, design project 1 was essentially a conceptual design, demanding creativity, the integration of a host of assumed basic skills and report writing (English is not the mother tongue of most black learners which obviously hampers their ability to communicate their ideas effectively in this language). Design project 2 was an application of robust design and marking of the reports focused on assessment of learner ability to apply the method, and not much on language and other issues.
4. A combination of explanations one to three.

It is proposed that the explanation for better performance of black learners towards the course end was mostly due to explanation 3, i.e. that racial stratification of results was removed by following an outcomes based approach. Had explanations 1 and 2 been true, similar results would have been obtained in other courses (e.g. MECN371, Figure 1), which is not the case.

From Figure 7 it follows that skills related to statistical calculations, FMEA and the application of the design process had been reasonably well acquired by learners. Skills associated with the application of force balance (basic mechanics) and functional analysis could not be convincingly demonstrated. The inability to apply basic mechanics accurately is worrying, but the author had found that performance in this category is strongly influenced by the nature of the problem and how it is formulated. The inability to master introductory functional analysis was probably due to the fact that learners had not been exposed to enough related examples and exercises. Regarding DOE and RDM, the average student had acquired the basic skills to an acceptable degree, which supports the hypothesis that these techniques can be taught to freshmen on a basic level. This conclusion is also supported by the fact that the average student successfully completed design project 2, which was devoted to design by experiment as explained earlier. An interesting feature of Figure 7 is the apparent racial equality of average learner skills for most outcomes. The "usual" distorted trend of Figure 1 did not manifest itself in this course (except perhaps for design project 1 and the class test). In fact, with regard to DOE and RDM, the average black learner slightly outperformed their white counterpart. It is plausible that the current almost "race insensitive" results are due to the fact that fundamental skills had been carefully identified, taught and assessed in this course. In courses where racial distortion of results manifest themselves, lecturers perhaps formulate and assess projects, oblivious of the fact that their completion requires integration of a host of fundamental skills that the disadvantaged hadn't been educated in.

The good performance of black females in this course was particularly noticeable (see the data for design project 2 and the final mark in Figures 5 and 6 and the exam scores in Figure 5). However, they constituted a small sample and hence their results should be interpreted with caution.

Figure 8 shows that the handful of learners who had acquired the course outcomes really well and passed with distinction, were white or Asian.

6. Conclusions and recommendations

This paper summarized the results obtained from adapting a freshman course in engineering design, MECN124 *Introduction to Mechanical Engineering and Design*. The syllabus was adapted to

1. Improve coherence of core content.
2. Include basic design by experiment as a powerful, generic design tool, known to improve design quality and time to market, thus fostering designer competitive edge.
3. Include basic design by experiment to add educational value to the design, build and test assignment, design project 2.
4. Carefully define course outcomes, attempting to place disadvantaged and traditional learners on an equal footing with regard to prior learning.

Analysis of course assessment revealed that:

1. Students vastly expand their engineering knowledge by conducting the ten practical projects.
2. It is indeed possible to expose freshmen to basic design by experiment and for the average learner to master the essential techniques adequately.
3. The performance of disadvantaged students is improved by following an outcomes based approach.

Reducing the total syllabus content is a change the author would consider for future course offerings. It is likely that the somewhat low average final mark was due to too much material being attempted, but it could also have been caused by lecturer inexperience in teaching the particular material. If some topics had to be deleted, the module on detail design and manufacturing may be considered as a contender as these topics are comprehensively covered in subsequent years. The extra lectures thus made available could be devoted to more examples, exercises and applications in the remaining topics.

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