

# IMPLEMENTING CDIO: SOME EXPERIENCES AND RESULTS

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## ABSTRACT

Today, demands on the modern engineer are such that a broader skill base is required than that traditionally associated with engineers, or indeed than that delivered by traditional engineering education programmes. The accreditation bodies have recognized this and organizations such as ABET, and more recently Engineers Ireland, have refocused their accreditation processes to 'outcomes based' assessment rather than knowledge based assessment. In simple terms it is not what one teaches, but whether one equips graduates with the core skills required of a practicing engineer. Many, if not all, of the required attributes resonate strongly with the learning philosophies of CDIO – Conceive, Design, Implement and Operate – an engineering education paradigm championed by a range of leading engineering educational institutes worldwide.

We report on the experiences of implementing some of the CDIO principles in a 'traditional' engineering programme and discuss the issues associated with this change. Three examples of CDIO implementation are considered in the paper, two drawn from the first year of the degree programme (the laboratory programme and an induction programme), and one from the third year and concentrating on the use of re-engineering techniques in the redesign of a commercially available product.

## 1. INTRODUCTION

There has been an ever-increasing concern amongst educators, and indeed within engineering industry, that graduates from professional engineering courses lack skills in areas other than the engineering sciences. Specifically, it was felt that new graduates were deficient in, personal, interpersonal and communication skills and also lacked an ability to transfer their engineering science knowledge into the constructed or manufactured object. The latter deficiency echoes strongly the findings of Bloom *et al* in their seminal study on learning behaviour [1]. Various documents [2-4] contend that this problem is due to a lack of balance in the teaching institutions between engineering practice and engineering science. The argument develops from the practice of engineering education in the latter half of the 20<sup>th</sup> century.

## 2. IMPROVING ENGINEERING EDUCATION

In the 1950's engineering was predominantly taught by distinguished former engineering practitioners. The decade also witnessed the introduction of engineering science to the curriculum, taught, in general, by a newly appointed cadre of young engineering scientists. The 1960's were golden years with a happy balance between the old practitioners and the young scientists. During the 1980's the now aging engineering scientists replaced the engineering practitioners with younger engineering scientists and the trend towards a science based education intensified. By the mid 1990's industry had recognised a growing gap between the skills of engineering graduates and those needed for engineering practice. Indeed during these years emphasis on 'soft' topics such as design, communication, and ethics had almost faded away.

These truths were first publicized in 1995 by the American National Academy of Sciences, who state specifically that undergraduate engineering courses in the US focus upon engineering sciences at the expense of engineering design education [2]. An ensuing debate in the US among the interested parties resulted in The Accreditation Board of Engineering & Technology (ABET) U.S.A publishing their document, 'Criteria for Accrediting Engineering Programs' 1997, followed by update documents [5, 6]. After a period of time, our home institution 'Engineers Ireland' (EI) produced its new guidelines for professional accreditation [7]. These guidelines, whilst reinforcing the value of engineering science in the curriculum, emphasize the necessity of students to have a growing understanding of, and competence in, the areas of communication, ethics, and multi-disciplinary team work. The EI requirements are embodied in six statements, but little, if any, guidance is given on how these aspirations may be achieved. Fortunately the EI guidelines almost completely match those of the ABET accreditation rules, the earlier introduction of which has bred a large number of publications on methods for their achievement in US teaching institutions [8-12].

In early 2000 a group of four universities applied to the Knut and Alice Wallenberg Foundation of Sweden to fund a bold venture that would reshape engineering education in the USA and Europe. This new model, called CDIO (**C**onceive-**D**esign-**I**mplement-**O**perate) [13] was to remove the failures previously described and provide future generations of engineers with the knowledge, skills and attitudes required to assume leadership roles in the twenty first century. Since 2000 CDIO membership has spread across all continents with some 30 participating institutions. The stated goals of the CDIO initiative are to develop:

- a deep working knowledge of technical fundamentals.
- a refined ability to discover knowledge, solve problems, think about systems, and master other personal and professional attributes.
- an advanced ability to communicate and work in multidisciplinary teams.
- skills to conceive, design, implement, & operate systems in an enterprise & societal context.

The CDIO belief is that graduating engineers should appreciate engineering processes, be able to contribute to the development of engineering products, and to do so while working in engineering organizations. The additional implicit expectation is that, as university graduates & young adults, engineering graduates should be developing as whole, mature, and thoughtful individuals. Thus CDIO has the same goals as ABET and so the publications of both give much guidance on the methods whereby Irish teaching institutions may achieve the improvements to engineering education required for EI for accreditation and more importantly for our student base.

### **3. BACKGROUND AND EXISTING CURRICULUM**

The Engineering with Management (formerly Manufacturing Engineering and Management Science) course is one of two engineering degree programmes available within the School of Engineering in Trinity College – the other being a general engineering course. The general course is long established (over 150 years) and leads to the BAI degree. In this course the first two years are common years, after which the students choose to take one of five different 'streams', of which mechanical and manufacturing engineering is one (the others being civil, electronic, computer, and electronic & computer). The Engineering with Management degree, BSc (Ing), is a newer programme (1<sup>st</sup> graduates in 2004) created to fulfil a need for engineering graduates with a broader knowledge base – allying business and management skills to the strong technical base associated with traditional engineering programmes.

The BSc course was modelled on the existing BAI (Mechanical and Manufacturing stream) programme, leveraging the direct entry nature of the course and the small class size (there is a quota of 20 students) to tailor the requirements to the specific objectives of the new programme. Because students begin their studies in the manufacturing domain (rather than having two years of general engineering) it was possible to realign certain teaching modules and replace others to significantly increase the business and management components. The programme has about 50% direct overlap (in that students take the same modules) with the BAI (mechanical) programme. While some areas of the course already have some resonance with CDIO, many do not. However, small class size and close control (the course is managed within one department rather than having to co-ordinate across the entire school), give the programme a high degree of agility with regard to implementing curriculum change. Three areas were identified for further implementation of CDIO concepts. A brief summary of the previous content/practice is given below. The changes introduced are detailed, and results are considered in subsequent sections:

- Introduction to Manufacturing Engineering
- First Year Engineering Laboratory Programme
- Third Year Design

### **3.1 Existing Curriculum – Introduction to Manufacturing Engineering**

The syllabus for this course was largely based on a manufacturing technology course taught to third year students in the BAI programme, and covered a wide range of machining and forming processes at a foundation level. The focus was on the technology, and relationships with the design curriculum were relatively unexplored.

### **3.2 Existing Curriculum – Laboratory Programme**

The students undertook the same laboratory programme as their BAI counterparts, consisting of 2 labs in civil engineering, 2 in electronic engineering and 2 in mechanical engineering (a tensile test and a pumping efficiency test).

### **3.3 Existing Curriculum – Design**

The design course consisted primarily of a series of lectures on design theory and, practice, and the use of standard components. Paper-based design exercises in design were followed, either as single-person or group activities, were undertaken.

## **4. MODIFICATIONS**

### **4.1 Introduction to Manufacturing Engineering**

As the students do not receive any instruction in design, or engage in any practical work related to the course until their second year, many have understandable difficulties relating what they learn in class to the broader context of product design, manufacturing and economics. Students are in effect requested to ‘learn on trust’ (that what they learn will make sense as other pieces of the ‘jigsaw’ are given to them over the programme duration). While the brighter and more thoughtful of the students may be able to contextualise the information received, many will not - a problem compounded by the relative intellectual immaturity of the majority of students at this age (17-18 years). Additionally, two of the main potential strengths of the situation – the small group size and the enthusiasm of a new cohort were not being adequately harnessed under the (largely podium based) teaching and assessment (end of year written examination) methods.

It was decided to introduce more group-based participative learning activities into the course, and to this end the following elements were introduced:

<b>Task &amp; Timing</b>	<b>Objectives</b>	<b>Content</b>
<b>Introduction</b> 1 <sup>st</sup> lecture	'Ice-breaker', Creation of group dynamics & class 'spirit', enunciation of motivations for taking this course, exploration of what manufacturing means	<ul style="list-style-type: none"> <li>• Groups put together to mix genders, background, experience etc.</li> <li>• Each group was given 10 minutes to assemble their thoughts.</li> <li>• Personal introductions</li> <li>• What manufacturing means.</li> </ul>
<b>Preliminary Design</b> 1 <sup>st</sup> lecture	Introduction to breadth of issues involved in design & manufacturing. Presentation Skills	<ul style="list-style-type: none"> <li>• Each group given a simple example product (a corkscrew, an adjustable spanner, a folding chair)</li> <li>• 15 minutes to prepare 4 slides– 1 each for 'how much will it cost', 'what is made of', 'how is it made' and 'what will it look like'.</li> </ul>
<b>Revised Design</b> 2 <sup>nd</sup> lecture	Introduction to breadth of issues involved in design & manufacturing. Presentation Skills Report Writing	<ul style="list-style-type: none"> <li>• After first lecture, each group was given two templates – (Word and PowerPoint)</li> <li>• Headings largely as above, but group had to identify a market for their product and include the implications of the market size on the cost estimates</li> <li>• Report 2 pages, Presentation 6 minutes, both delivered 1 week later at 2<sup>nd</sup> lecture</li> <li>• Class encouraged to give feedback to each other, as well as receiving feedback from staff</li> </ul>
<b>Final Design</b> End of 3 <sup>rd</sup> week	Decision making processes in product design and manufacture Presentation Skills Report Writing	<ul style="list-style-type: none"> <li>• each group required to take on (re-design of) another groups product</li> <li>• 2 weeks to prepare a 10 minute presentation and 6 page report</li> <li>• Encouraged to critique the previous design and note improvements</li> <li>• Marks awarded for both report and presentation with bonuses for the best report and best presentation</li> </ul>
<b>Informal feedback</b> Immediately after above	Informal introduction to staff Detailed feedback & discussion on exercise	<ul style="list-style-type: none"> <li>• Immediately following the presentations a short(ish!) reception was held</li> <li>• Overt purpose purely social, but considerable scope to discuss the above exercise in more detail.</li> </ul>

**Table 1 – Introduction to Engineering Exercise**

#### **4.2 Laboratory Programme**

Several limitations were apparent with regard to the existing programme – notably that:

- The lab content (e.g. civil engineering) was not always relevant to this programme
- Even where relevant, scheduling requirements meant that the majority of the class were doing experiments a significantly long time either before or after they had learned the corresponding material (e.g. yield strength of materials) in class
- The large class size (~200 students) meant that there was a significant boredom factor for the graduate students running the lab, as typically it had to be run 50 or so times per year. This was often readily apparent to the students who therefore had little 'buy-in' to what appeared to them to be a formulaic exercise.
- There was little or no opportunity for creativity on the part of the students in terms of how the experiment was conducted
- The equipment used was often old and rarely resonated with the students (naive!) concepts of what engineering was about

- There was relatively little coordination between different departments with regard to the overall laboratory programme objectives, and the requirements for individual lab reports.

Having taken the above limitations into account, it was decided to replace the programme with one specifically tailored to the BSc (Ing). The objectives of the new programme were:

- To be accessible (in terms of their existing knowledge base) to the students
- To be fun and thought-provoking
- To allow creative input in terms of how an experiment was conducted
- To introduce the students gradually to the production of quality engineering reports
- To develop an understanding of how to gather, analyse and present data
- To understand the concept of experimental error, both in how and where it arises, and how it may be quantified
- To introduce data acquisition and calibration methodology and equipment.

The new programme consists of 5 separate laboratory sessions, each of which make use of LEGO Mindstorms™ kits. Mindstorms take the existing LEGO Technical range (which incorporates gears, motors, axles etc in addition to the ‘standard’ building blocks) and add a programmable control ‘brick’ and sensors (ultrasound, touch, sound and light). The programmable brick allows for bi-directional communication with a PC via USB or Bluetooth. The control brick has on-board RAM and is capable of storing programs and data which may be uploaded or downloaded to the PC. The software environment was developed by National Instruments and has much in common with their LabView™ suite.

The five labs are as follows:

- **Introduction** –students are given instructions on how the software works and some simple tasks to perform – involving construction and programming of a very basic robot.
- **Calibration Design** –students are given information on calibration techniques and theory and asked to conceive and design an experiment to calibrate the ultrasound sensor for use as a distance measurement device. They are allowed to use any equipment or materials that they wish to source themselves. Feedback is given during the session on any ideas, from both the demonstrator and academic staff, and students are encouraged to physically implement ideas, where possible, on a trial basis.
- **Calibration Implementation** –students are required to implement their experiment and to calibrate the sensor. A report template indicating the information required – broken down into boxes, each requiring a paragraph of text - is given to each student.
- **Measurement Design** –students are asked to design an experiment to measure the perimeter and surface area of a box. Further information is provided on the theory of experimental error. As with the 2<sup>nd</sup> laboratory, feedback on suggestions is given and active trials are encouraged.
- **Measurement Implementation** –students are required to implement the lab they had designed in the 4<sup>th</sup> session and to produce a report outlining their results, inclusive of error analysis. A list of required headings for the report is given, but not to the level of structural detail provided in the 3<sup>rd</sup> lab.

### 4.3 Design

The outcomes from the pre-existing exercises were somewhat unsatisfactory because of the students unsurprising lack of ability in embodiment and detail design. The unrewarding nature, for both students and staff, of these exercises motivated the changes described below.

Formal design teaching is compressed into years two and three of the course. In semester I of the initial year students spend their time learning and practising the fundamentals of engineering graphics and some CAD. The purpose of this is not to train them as draughts-people, but rather to get them to the stage where they can 'read' an engineering drawing and understand the importance of such aspects as dimensional and geometric tolerances, bills of materials (BOM) etc. Semester II of this year introduces the students to the methodology of engineering design. The path followed here is that of systematic design, the reasons for adopting the approach have been given in a previous paper [14] and are supported by the work of others [15-17]. The general methodology is well described in VDI 2221 [18] and it has much to recommend it, in that it allows the student to break down a design problem into blocks which may more readily be solved. Furthermore, the technique of creating a number of 'Concept Variants' (candidate solutions) allows the student to iterate when problems surface. After this approach has been absorbed by the students, open ended design projects may be posed for individual solution. The students are encouraged to discuss the expansion of the specification and 'task clarification' in groups and to use formal group methods for these exercises. Their design concept ideas are often very clever but their design will, in general, fail due to ignorance of the details of manufacturing technologies and of the availability and form of standard components. These failings often leave the student with a sense of underachievement and need to be discussed in a sympathetic way. Obviously students achieve only the C and D aspects of CDIO in this design exercise. These failings are addressed in the following year of design experience.

In the first semester of the next year, the function of standard components in mechanical engineering is explored. Here the fundamental equations of interaction of these components are described and the relationship and effect of these components as 'auxiliary functions' in a design is expanded upon. The legal and regulatory rules that attend their use are also explored. The decomposition of CAD databases for the purposes of manufacturing strategies (CIM etc) is also taught. Semester II sees the teaching of re-engineering philosophy and methods. The technique is elegantly described by Otto & Wood [16]. There then follows a team-based project on re-engineering. This project takes a chosen commercial product and requires the students to follow the method and make design improvements, whilst taking care to comply with all Standards and regulatory issues that are relevant. Teams are composed of 3 or 4 members randomly chosen from the class and each team, once formed, democratically elects a team leader. All teams are given the same commercial product on which to focus their efforts. They then, as teams, begin the re-conceptualisation of the device in order to define its 'perfect' state - without price constraint. On completion of this phase the team leader then devolves various tasks to individual members. The members then concentrate on their individual tasks, market survey, BOM, Remove & Operate, regulatory/standards issues, evaluation of components etc., whilst also reporting on their work at regular team meetings. All team deliberations are recorded. Finally as a team they implement re-design of the product, this may occasion removal or addition of components, ergonomic redesign, market considerations etc. The evaluation process of each teams work is described in 5.3.

## **5. RESULTS**

### **5.1 Introductory exercise**

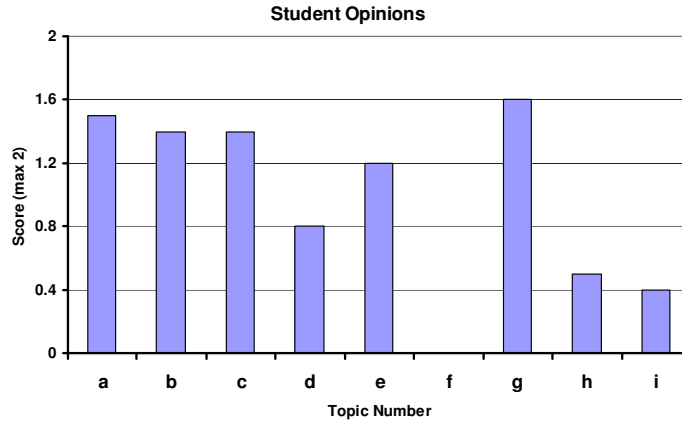
Results for the introductory exercise are somewhat difficult to quantify explicitly, particularly since there was no prior analogue. However, the following observations may be pertinent:

- Students were not previously required to make oral presentations until in their 3<sup>rd</sup> year. The ‘sudden immersion’ experienced in the first lecture means that students perceive this to be just another part of a new learning paradigm. With expectations necessarily relatively low for the first presentation (short preparation time, limited knowledge and resources etc), the ‘first time’ experience is dealt with quickly and with a minimum of stress. Students were notably more animated, capable and relaxed on subsequent presentations. It is to be expected that the skills learned and feedback obtained will be of considerable benefit to the cohort when required to make presentations later in their degree programme.
- During subsequent ‘traditional’ lectures, students appeared more willing to ask questions and engage in discussion. The exploration of the wider issues involved in manufacturing (e.g. relationship with design and economics etc) was reflected in these exchanges.
- The template used to initiate the report writing exercise, combined with the iterative nature of the exercise, helped the students move gradually towards writing a useful technical report without feeling overwhelmed or intimidated by the task.
- The competitive element, particularly with regard to the final iteration (where each group ‘swapped’ their ‘pet product’) worked especially well, as students naturally found themselves engaging in the analysis and evaluation phase of Blooms Taxonomy [1] – something which is notably difficult with traditional ‘chalk and talk’ format learning.
- The social event immediately succeeding the exercise provided a very useful opportunity for feedback from both staff and students. Many took the opportunity to explore details of the programme about which they were unsure or curious.
- The nature of the first day exercise helped to break down social barriers, engender a cohesive class-spirit and assist the students in adjusting to a radically different environment.

## 5.2 Laboratory programme

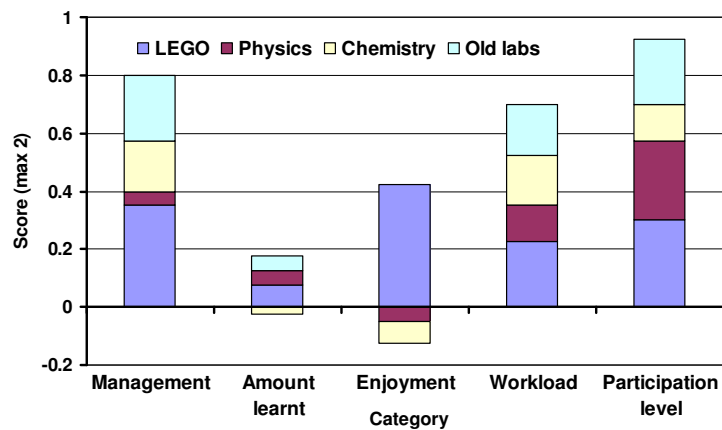
The results of the laboratory programme were assessed using the marks awarded to the students for their individual lab reports, as well as through an electronic questionnaire, anonymously completed by the students. This questionnaire examined both the students attitudes the LEGO labs as a self-standing entity and also comparatively – with their Physics and Chemistry labs (and in the case of three repeating students, the previous first year laboratory programme). The marks obtained in the lab reports were higher than those received in previous years, but further conclusions are difficult to draw due to the radically different nature of the lab group and (possible) differences in attitude and/or ability between year groups. In part 1 of the questionnaire, students were presented with a range of headings referring to the new LEGO programme and were asked to choose from 5 different categories indicating how they felt about each topic. The questions were scored from -2 to +2. A sample of the questions and responses is shown in Figure 1.

- |                                    |   |
|------------------------------------|---|
| (a) Teamwork                       | (f) Perceived benefit across degree programme |
| (b) How to design an experiment    | (g) Enjoyment                                 |
| (c) Sources of experimental error  | (h) Intellectually challenging/stimulating    |
| (d) Dealing with errors            | (i) Amount learnt                             |
| (e) Usefulness of report templates |   |



**Figure 1 - Student Opinions of new LEGO labs**

The results are overwhelmingly positive, albeit a degree of ambivalence is reported with regard to the amount learnt & the perceived benefit to the degree programme. In the second part of the questionnaire, students are asked to make a comparative assessment of the new LEGO labs compared to their other labs (Chemistry, Physics, and in the case of repeating students - their previous first year engineering labs. The results are presented in consolidated form in figure 2.



**Figure 2 – Comparison with other 1<sup>st</sup> year labs**

The height of each bar represents the average across all labs, and the proportion of each bar shows the relative merits of each lab in that particular category. The most obvious inference that can be drawn from the results is that the students are significantly more positive about all aspects of the new programme (most notably in the case of enjoyment where the LEGO labs was the only one they found enjoyable!) This is in keeping with the sense of enjoyment reported in part 1 of the questionnaire, as is the perception that they learnt relatively little (albeit more than in other labs

### 5.3 Redesign assignment

The results of the redesign project are assessed for grading in a variety of ways. Each student is interviewed three times and their work up to the date of each interview is evaluated. On conclusion of the project each team makes an oral presentation of 30 minutes duration. Each

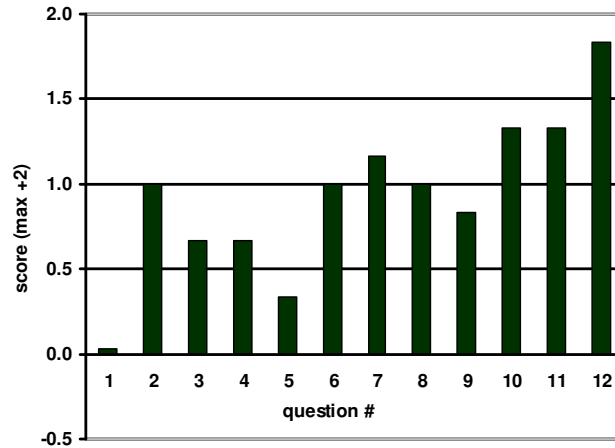


team member presents on an aspects of the re-design, book-ended by the team leader giving an introduction and conclusions. A period of questions from a panel of three staff completes the assessment process of the oral. Overall team marks are awarded under three headings, re-design, project planning, and quality of communication. Finally a design portfolio is produced by each team and this is evaluated. An overall mark is given for the portfolio work, this value is awarded equally to each team member with the team leader been given a 10% bonus for his/her extra efforts. The marks are then compounded in the ratios 15% interviews + 25% oral + 60% portfolio. This forms the largest aspect of marks in the subject for semester II.

Q	question score value	-2	-1	0	1	2
1	Redesign notes were useful in pursuing the project	No use	useful but lacked sufficient detail	useful	necessary	perfect for task
2	I now understand the value & function of re-conceptualization	Not at all	poorly	reasonably	well	very well
3	I now understand the value & function of a customer/market survey	Not at all	poorly	reasonably	well	very well
4	I now understand the value & function of the BOM process	Not at all	poorly	reasonably	well	very well
5	I now understand the value & function of the ROP process	Not at all	poorly	reasonably	well	very well
6	I now understand the value & function of the re-Design process	Not at all	poorly	reasonably	well	very well
7	working in teams was:-	of no value	sometimes useful	helpful	helpful & stimulating	an integral part of the process
8	the project brought me in contact with a real world design problem	not at all	a bit	yes	yes & made me think about design	yes, made me think about & see the value of good design
9	the project will help to improve my team skills	not at all	a bit	yes	yes but I did not enjoy it	yes & made me see the value of team effort
10	the oral presentation will help to improve my communication skills	not at all	a bit	yes	yes but I don't enjoy the speaking bit	yes & will make me see the value of this aspect
11	The exercise was:-	neither enjoyable nor	tolerable	educational	sometimes enjoyable & educational	very enjoyable & educational
12	I recommend the redesign project be continued	definitely not	no opinion	yes but with changes	yes	most definitely

**Table 2 - Student questionnaire**

Of perhaps more interest is how the students themselves view this approach to design teaching. This is assessed by the use of a questionnaire completed anonymously by each student. The questions asked are shown in Table 2 and the results to date are displayed in Figure3. From figure 3 we can see that the group response is wholly positive and generally significantly so. Responses to questions 6-12 are most encouraging; not only are the learning outcomes perceived to be present but the module was considered to be valuable, enjoyable and its retention for future students is strongly recommended by the present student cohort.



**Figure 3 - Compounded Results from questionnaire**

The result for question 1, (printed notes on the topic) is disappointing as these notes form a significant guide to the methodologies to be used, this failure may also explain the relatively poor score for question 5. It is hoped that with some changes and perhaps more question-and-answer periods during class that new responses will all tend strongly toward a value of +2.

## 6. CONCLUSIONS

Examples have been presented of curriculum revisions made with the purpose of making an engineering degree more CDIO compliant. These initiatives have been varied in scope and ambition and applied at both the earliest and later stages of the students' education. The results have been largely very positive. Exceptions to the above observation can be thematically grouped in terms of the amount that students feel they learned during the exercises. There is a notable divergence between the perception of staff and students in this regard – with staff feeling that there were substantially improved learning outcomes from the new initiatives! Whilst there are undoubtedly aspects of each initiative that can be improved, it is suggested by the authors that this divergence is due, at least in part, to the compartmentalised and examination focused expectations that students have, particularly in their earlier years of third level education. Every exercise and undertaking is viewed primarily in terms of how it relates to examinations, and unless an exercise directly requires or develops applied knowledge related to examination material it is perceived as a chore to be dispensed with. It will require sustained effort on the part of staff to nurture a more mature view of the educational process, and in this regard a planned follow-on study with the same students in later years will be instructive. Notwithstanding, close scrutiny of the exercises needs to, and will, be undertaken to assist in increasing the (perceived and actual) relevance of the subject matter.

In conclusion, it is the authors' contention that CDIO implementation should be seen as part of a holistic and continuous process of curriculum development. There are significant efforts required to implement such changes, and a transition to a 'fully compliant' CDIO framework is a long term project. For those institutions (probably most of us!) that are in the early stages of implementation, it will require both determination and a willingness to be an early 'champion' of the new paradigms. We must bring even our unwilling colleagues with us. Nonetheless, the benefits, only some of which are touched on here, are apparent – not least in the greater enjoyment and learning for staff and students alike.

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