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The principles of mechanics for students of product design

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The principles of Mechanics for students of product design

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Those engaged in product design need to combine creative talent and sensitivity with intellectual ability. The Carter report on Industrial Design Education in the United Kingdom¹ identified the ideal 'A'-level subject combinations as 'traditional academic subjects, such as Maths, Physics or English, in addition to the more specialised design subjects' — a position which the Design and Technology department at Loughborough University of Technology (LUT) would wholeheartedly support. This article concerns the application of the principles of mechanics by students of product design, but could probably equally well have been written about electronics, materials science, ergonomics, or communication techniques. Without the full integration of these disciplines product design becomes an undemanding activity and if Craft, Design and Technology (CDT) in our secondary schools does not promote such integration then the subject loses its credibility. The new General Certificate of Secondary Education (GCSE) National Criteria have allowed three categories 'CDT: Design and Realisation', 'CDT: Technology' and 'CDT: Design and Communication', and although they are all headed 'CDT' and no doubt reflect the available human and physical resources in schools this appears to be an unfortunate expediency. It is regrettable that the opportunity to radically review the CDT examination structure and promote a unified subject area to provide a sound foundation for growth has not been fully grasped. There is a clear invitation to emphasise 'Design and Realisation', 'Technology' or 'Design and Communication' at the expense presumably of the others. The Northern Examining Association (NEA) have clearly risen above the disorder which has been facilitated by the GCSE National Criteria and aggravated by the Schools Council Modular Technology resources to produce a 'CDT: Technology' syllabus which I can do nothing but praise. I have yet to see any other syllabuses showing the same enlightened approach and in the long term I can only hope that this provides the model for all GCSE CDT syllabuses in schools. The approach adopted for

this new examination syllabus is discussed later in this article.

Product design has always provided students with opportunities to apply the principles of mechanics whether the force systems are static or dynamic or the resisting materials more solid than fluid. Static force systems, their equilibrium and stability with external disturbances, are important to every furniture designer, boat builder and frame constructor; the concepts of an object's degrees of freedom and restraint are central issues in the design of all clamping devices and mechanisms. An understanding of dynamic force systems, the concepts of work, energy and power, is crucial to the analysis of any machine — from the power transmission system of a bicycle to a computer controlled lathe. In transmitting and resisting forces, materials are influenced by them resulting in elongations and deflections, pressure and volume changes and potentially immediate or long-term system failures. Understanding and controlling the response of materials to forces in the working environment is the essence of designing products to be safe and reliable, and provides the basis for sound material selection in the light of manufacturing requirements.

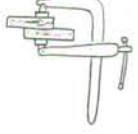
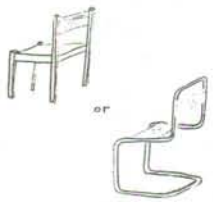
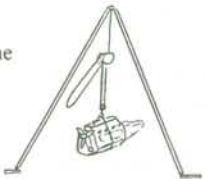
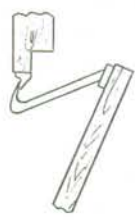
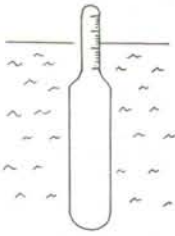
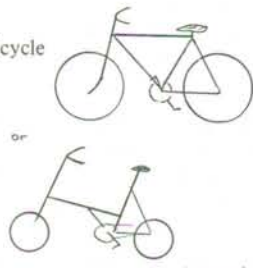
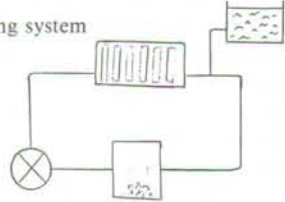
Table 1 indicates a range of products together with questions the designer should ask and be able to answer. The designer might well think the answers to other questions to be more important, for example in the case of a hydrometer the question of what type of scale is fit for its purpose might be considered to be the dominant issue and not the precise relationship between the scale divisions and the fluid density, but fitness-for-purpose is hardly likely to be satisfactorily resolved if the designer does not understand the fundamental relationship.

Mechanics within CDT

Product design is the central element of CDT — one of the fastest growing subjects in the secondary school curriculum. It might therefore be expected to find evidence of growing links between CDT and Mathematics and Physics departments and the application of the principles of mechanics, wherever learnt, to be evident in CDT projects. My contacts

with schools and teachers gave little reason to believe that either is happening. A recent discussion paper² by two HMIs is not much more optimistic. The recent CNA/SCUE report of 'A'-level Design and Technology³ — 'The Identification of a Core Syllabus' saw little virtue in reviewing the historical routes by which we have reached the present position, seeing the current syllabuses as an expression of the views of the individuals and groups who have acted as pioneers. 'Rather it is far more important to establish the opportunities created by the subject and to keep these clearly in mind as the detail of a core experience is fashioned into published examination syllabuses'. As an assessment of priorities this view is plainly accurate, but tends rather towards the 'all history is bunk' philosophy which provides a very positive prescription for progress whilst ignoring the lessons which time has revealed, albeit in different circumstances. As these lessons are central to understanding the strange position of mechanics within CDT I shall indulge in a little bunk!

Conceptually there seems to have been little advance in thinking with regard to technology in schools since the late sixties. All the key elements of the recent SCUE report on 'A'-level Design and Technology can be found in Malcolm Deere's article published in 1969 — 'A'-level Technology, a liberal approach.⁴ The proposed syllabus in 'Technological Studies' he suggests has three sections. Section I classifies the knowledge base under 'Materials', 'Energy' and 'Systems', which still seems to me a better classification than 'Materials and Components', 'Energy', 'Control' and 'Technology and Society' as proposed in the SCUE document. The design process is seen as a 'system under human control' which seems plainly superior to the CNA/SCUE version, where it is classified as a skill or technique. As Malcolm Deere stated social and industrial systems can be studied alongside thermodynamic, electrical, biological and mechanical systems and the 'Technology and Society' category seems somewhat redundant. Section II contains the essential ingredient of analysing existing products and the influences upon them

PRODUCT	SKETCH	SOME KEY QUESTIONS
Carver cramp		<ul style="list-style-type: none"> — when will the clamp slip? — which dimensions are critical? — how great will the frame deflection be?
Chair		<ul style="list-style-type: none"> — what loads must be supported? — how will they be transmitted through the structure? — how great will deflections be? — how can the likelihood of failure be adequately reduced?
Lifting frame		<ul style="list-style-type: none"> — will the shear legs buckle? — is the wire strong enough? — could the feet slip? — will one person be able to lift the engine?
Cupboard safety catch		<ul style="list-style-type: none"> — what age child can open the catch? — what is the best cross-section? — will the material fail under repeated flexing?
Hydrometer		<ul style="list-style-type: none"> — what kind of scale divisions would represent fluid density? — will the hydrometer overturn too easily or oscillate excessively? — will the instrument be sufficiently sensitive?
Electric bicycle		<ul style="list-style-type: none"> — what are the implications of various motor placements? — what are the relative advantages of Moulton and diamond frames? — do the cross-sectional shapes affect wind resistance? — what size motor is necessary to assist a senior citizen up a 1 in 20 incline?
Heating system		<ul style="list-style-type: none"> — what size pump do I need? — what difference does the pipe diameter make? — how many radiators are necessary and what size boiler?

and Section III suggested an open-ended group project of the schools' own choice. The lessons of the last seventeen years are not those concerning framing a syllabus or classifying knowledge, but the experience of attempts at 'realisation'. Ignoring them makes about as much sense as designing Mark II without a full analysis of the limitations of Mark I.

Apart from the general status problem of engineering, industry and workshops school technology has tended to founder on the political problems associated with having the means for the realisation of designs centred in the CDT department whilst the analytical processes necessary are seen as the province of the Mathematics and Science departments. My experience of school departments is limited, but they appear to be run as 'empires' and are very territorial — it is only the bold and determined departmental head who ventures past their traditional subject boundaries. To illustrate the significance of these difficulties consider the chequered history of one of the oldest 'A' level syllabuses in this area, in fact dating from 1966 — the University of Cambridge Local Examination Syndicate, Elements of Engineering Design. From the mechanics point of view this syllabus is far more demanding than its more esteemed potential successor — the 'Materials' and 'Structures' modules from Cambridge Technology. In the older syllabus students had to consider mechanisms and the analysis of dynamic systems under 'Mechanics' as well as structures, and under 'Related Technology' materials science investigations and engineering components as well as the structure, properties and processing of materials. The 'Testing of Structures' and 'Industrial Manufacturing' sections of the Cambridge modules would however have been welcome improvements to the older syllabus. The Elements of Engineering Design syllabus has been successfully implemented in many schools, but has never really grown beyond a hundred or so candidates or achieved proper recognition outside schools. SCUE did include this syllabus in the list of those 'A' levels incorporating elements of design which should be given full

recognition for the purposes of the general entrance requirements (1979)⁵ and it did gain recognition from the Northern Universities Professors in Mechanical Engineering (1979),⁶ but appears to have fallen foul of the committee which judged it against the Keith-Lucas criteria published by the Design Council in 1980⁷ — criteria which Cambridge Technology apparently meets.

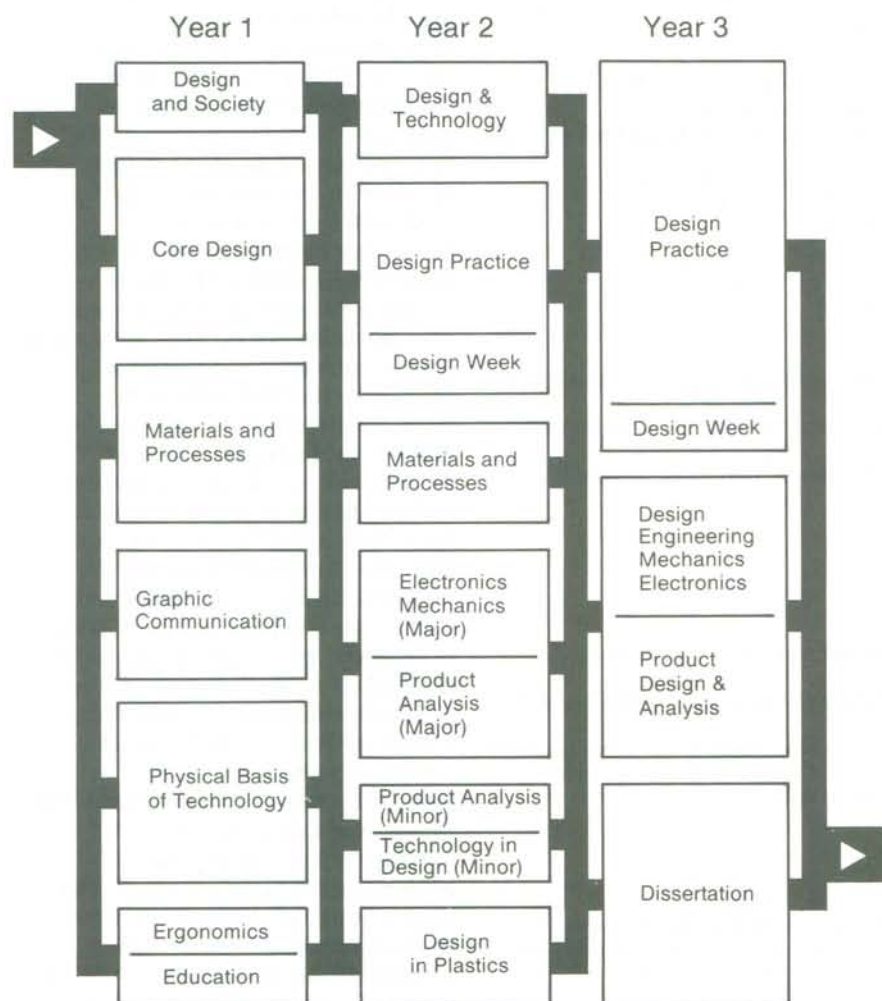
The reasons for this peculiar state of affairs can be found in the departmental structure of secondary schools. The Elements of Engineering Design 'A' level is generally taught within CDT (Technical Studies) departments and is essentially workshop based. It therefore fits quite naturally alongside such subjects as Mathematics and Physics at

'A' level without 'friction' and the teaching of the mechanics can be tailored to follow the theoretical coverage given in the Mathematics and Science departments. The syllabus fits the traditional school structure at the cost of a certain narrowness which is no doubt the reason for its rejection by the Design Council despite its academic credibility. A workshop based 'A' level is also certain to carry a 'dirty hands' image which is why the current proponents of 'A' level Technology have tended to prefer 'laboratories' with the inevitable emphasis on electronic and pneumatic systems. The 'Structures' and 'Mechanisms' modules are introduced into the laboratory as a kind of token gesture to the mechanical world whilst the wealth of opportunity abounding

for the sound teaching of mechanics in school workshops is ignored. Whatever their intentions those who try to draw the study of mechanics from the workshop to the laboratory in the search for academic credibility are reinforcing the 'English Disease'.

Malcolm Deere indicated the way forward in 1969 and the recent CNA/SCUE report and the sympathetic changes to the London Design and Technology 'A' level are following the same lines. No real progress will be made however until the aversion of schools and part of our society to industry and commerce and, in this case to the tools of production is shown up for what it is — a kind of small-minded elitism.

FIG. 1 Design and Technology 3 year BA Honours at Loughborough University



Design and Technology 3 year BA Honours

The Content of Undergraduate and In-Service Courses

It has always been apparent that product designers need a clear understanding of the principles of mechanics if they are to effectively exploit technological know-how. Fig. 1 shows the structure of the Design and Technology 3 year BA Degree and all students in Year 1 study the 'Physical Basis of Technology' which has two components — mechanics and electronics. The mechanics syllabus includes an introduction to the study of statics and dynamics for both solids and fluids. The development of an understanding of technological systems is incorporated for all students in Year 2 as 'Minor Technology' and hence all students whether they opt to major in 'Technology' or 'Product Analysis' have the necessary foundation for 'Design Practice', the designing and making component of the course.

In-service courses however present much greater difficulties. Two approaches to the introduction of technology into the school curriculum have gained significance acceptance, namely its teaching as a 'single-subject' and the enrichment of existing courses,⁸ and modular resources have been developed to promote both. At primary schools, children meet all aspects of mechanics through kites, boats, rockets (made from plastic bottles) and vehicles of all descriptions. Interestingly as the children get older, and certainly as external exams appear the concepts covered narrow. At CSE and 'O' level

'Structures' and 'Mechanisms' modules exist ('Aeronautics' was one of the earliest proposed and was eventually to be published in 1986) and for Cambridge 'A' level Technology only 'Structures'. Many GCSE syllabuses do not appear to have significantly altered this position, but the NEA GCSE 'CDT: Technology' certainly has. This syllabus has divided the subject content into two areas, 'skills' and 'knowledge'. The skills section is further subdivided into design and problem solving, product realisation and communication and the knowledge section is divided into systems, energy considerations applicable to a particular system and the selection of materials and components for systems. Knowledge of mechanisms and structures is incorporated naturally at the appropriate places. Such a systems approach is wholly sound and detailed criticisms of the particular choice of components would always be possible but is unnecessary. The conceptual levels of difficulty for raising a load and a conveyor are excellent as is the list of possible projects. Here we have a full integration of technology into product design — lucky students! 'Mechanisms' has re-emerged linked to 'Energy' as an option in the London, Design and Technology 'A' level syllabus, with a basic coverage of these and structures in the core. In view of this emphasis it had been felt necessary to

follow the schools and for the major course component to be 'Structures' and to cover 'Mechanisms' to a much lower level. As the teaching of technology is predominantly in the 14-16 age range and not in the foundation years the emphasis has also been placed on work for C.S.E. and 'O' level and now G.C.S.E.. Table 2 shows the structure adopted at LUT for the third One-Term In-Service course, 'OTIS 3' in Design and Technology, but this has now been revised for the forthcoming 'OTIS 4'.

For those teachers able to cope with the necessary mathematics this course structure seems to have worked satisfactorily, but for many, 'O' level mathematics was somewhat distant and rarely had been utilised. Consequently even the elementary work on 'Structures' — resolving and adding forces — was a source of some difficulty. Some teachers have suggested moving the 'Primary school mechanisms' forward from Week 6 and brushing-up the necessary mathematics, which will be done in future, but it is clear how little mathematics is currently used in the CDT world. Studying statics before dynamics, or structures before mechanisms, provides a more logical ordering of concepts, but as the approach adopted is one of understanding and classifying mechanisms through 'hands-on' experience of construction kits, there is

very little lost. The suggestion made in the Mechanisms module that the Structures module, or at least the concepts, should be covered first is perhaps unnecessary. The popularity and early dominance of 'Structures' is really more associated with the ease of graphical methods like Bow's notation in comparison with say the method of instantaneous centres for mechanisms and the available know-how of the teachers from earlier Technical Drawing syllabuses. For comparison and to illustrate what we believe we have learnt with the help of the teachers taking the OTIS courses, Table 3 shows the anticipated structure of 'OTIS 4' mechanics. A formal support class has been programmed, although much of this took place informally during OTIS 1-3, and the course is now in 'chronological' rather than 'conceptual' order. We have also been able to introduce Pneumatics as the MSC via British School Technology have recently made some capital money available to the University for in-service courses. It is hoped that this will provide a suitable introduction for teachers embarking on the new GCSE syllabus.

A Fundamental Review

It was encouraging to see the SCUE recommendations for a core syllabus in 'A' level Design and Technology using the word mechanics alongside

TABLE 2 One-Term In-Service Mechanics (OTIS 3)

WEEK	LECTURE	PRACTICAL ACTIVITY
1	Mechanics in the school curriculum and 'Modular technology'.	Using spring balances and the graphical analysis of forces.
2	Mathematical modelling — friction theory and modelling the performance of friction devices.	Testing the theory using inclined planes and applying it to carver cramps.
3	Structures — finding reactions. Bow's notation and analytical methods.	External equilibrium of a meccano frame and graphical statics.
4	Designing tension and compression members.	Materials testing — tensile, compression and hardness.
5	Designing beams for strength and stiffness.	Chair crushing contest and the use of strain gauges.
6	Primary school mechanisms — 'uphill', 'downhill' and 'wheels and gears'.	Fischertechnik and Lego Technic investigations of gearing and the meaning of torque.
7	Mechanisms — the approach for the 14-16 age range.	Fischertechnik and Lego Technic CSE & 'O'-level assignments.
8	Work, power and energy — applying the concepts.	Investigation of the energy stored in an elastic band.
9	Model hill-climb vehicle — integrating the concepts of statics and dynamics.	Hill-climb vehicle construction and testing.

ergonomics and materials etc. The subdivisions of mechanisms and structures are unhelpful within the context of product design, although in providing supporting resources they are no doubt useful titles. The 'Structures' module begins by asking some rather superficial questions concerning the types of forces in a bicycle frame, but the joints are hardly 'pins' and the members contain combined loadings — for most of the questions almost any answer will do! It moves on from here to the analysis of roof trusses and Warren girder bridges, and although children may have used or can be given spring balances to measure small forces very few have any concept of 10kN wind loads. What makes this kind of approach even less appealing is that the analysis of any vehicle, bicycle or otherwise, performed in depth provides the opportunity for the exploitation of almost every principle of mechanics. Energy requirements, power and its

transmission, steering and braking systems, dynamic loads and the structural design of the chassis provide all the scope any teacher could require. Oval bicycle frame tubes, solid wheels, racing suits and helmets even provide opportunities for the examination of fluid flow. The abandonment of fluids by secondary schools is particularly regrettable in view of the excellent work which has been done — the testing of model hovercraft was amongst the earliest projects conducted under the technology umbrella and the construction of single seater racing hovercrafts has provided excellent constructional projects in schools with both original designs and the professionally developed Cyclone, but even this has produced a multitude of customised versions.⁹ Project Technology produced two books in this area in the early seventies 'Simple Fluid Flow' and 'The Ship and Her Environment'. What a tragedy that the

examination system has reduced such a wealth of opportunity and challenge to the tamed and inhibited analysis of 'Structures'. The NEA GCSE 'CDT: Technology' syllabus by adopting a systems approach to product design is leading the way back in our schools.

The fundamental requirement is for the application of the principles of mechanics in the design and realisation of products — in the workshop. Any attempt to move the subject away from its roots should be resisted and the academic snobbery which makes this movement seem reasonable should be exposed. In CDT departments the application of the principles of mechanics should be concerned with two areas — firstly, the proper understanding of the tools of production and their effective use, and secondly, in the design analysis and development of safe reliable products meeting the defined need. This seems to be true whatever level of education is

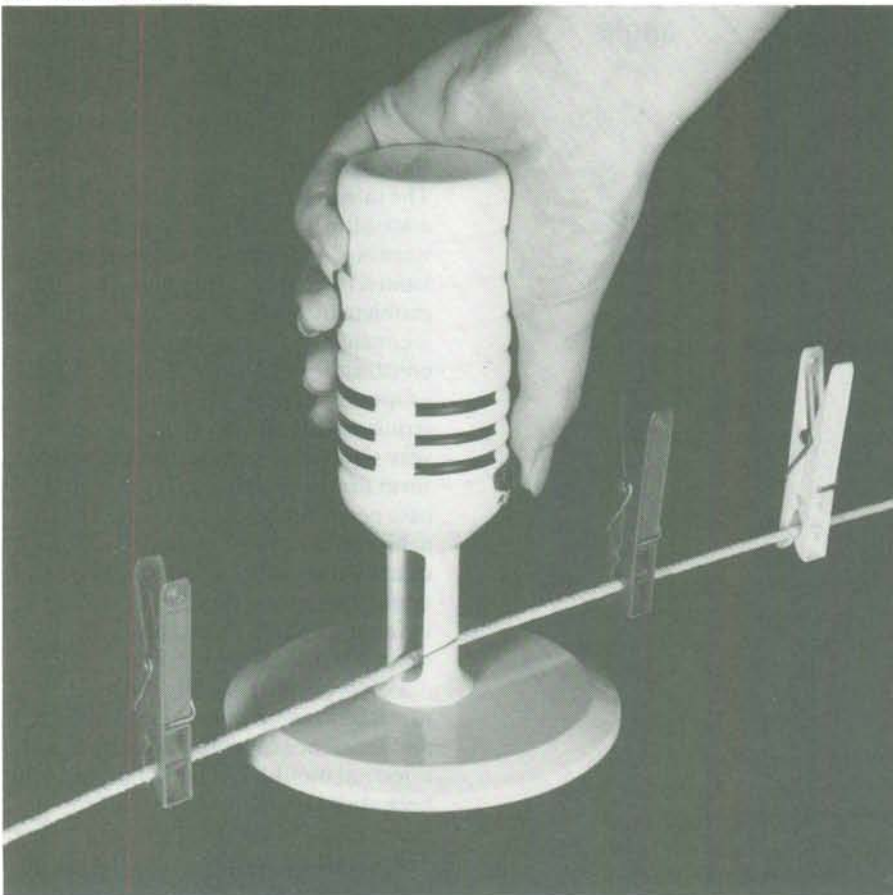
TABLE 3 One-Term In-Service Mechanics (OTIS 4)

WEEK	LECTURE	PRACTICAL ACTIVITY	SUPPORT CLASS
1	Mechanics in the school curriculum — its place in the new GCSE syllabuses.	Primary school mechanisms Lego Technic and Fischertechnik assignments.	Assumed knowledge for the technology modules. Choosing and using a calculator, symbols and units, indices, scientific notation.
2	Mechanisms — the approach for the 14-16 age range.	Mechanisms for 14-16 yr. olds. Lego Technic and Fischertechnik assignments on levers, gearboxes and steering.	Greek Symbols Trigonometry.
3	Forces and the 'Structures module' approach.	Measurement of static and dynamic friction. The effects of lubrication. The application of friction and the jamming principle.	Application of trigonometry to mechanics. Vector representation of forces.
4	Frameworks and external equilibrium	Graphical statics Building a statically loaded framework.	Functions and graphs.
5	Internal forces and evaluation techniques.	'CSE' Control Technology — linear motion using solenoids and pneumatic cylinders.	Gradient and enclosed area of graphs e.g. load vs deflection.
6	Beams — designing for stiffness and strength.	Pneumatics module I — cylinder control devices.	Substitution and transposition of formulae.
7	Materials testing and structural design.	Pneumatics module II — automatic circuits.	Acceleration, velocity and distance curves and equations.
8	Work, power and energy	Strain energy of an elastic band and two bands in series and in parallel. Conversion of strain energy.	Quantitative approach to Mechanics I.
9	Hill climb vehicle.	Hill climb vehicle construction.	Quantitative approach to Mechanics II.
10	Alternative sources and the 'Energy module'.	'Power for Elaskay' — case study.	



FIG. 2 Helical flower pot stand

FIG. 3 Rain detector



chosen and was probably often being quite effectively done under the 'Craft' label in schools and colleges before the current technology bandwagon started rolling. There can however be no excuse for living in the past, computers are radically influencing both the design and manufacturing processes and every possible opportunity to introduce CAD/CAM into CDT departments must be taken. Computers are not however an excuse for disguising the workshops of the schools to look like laboratories — what can such attitudes do for the workshops and factories of the nation.

Two Case Studies

Fig. 2 and Fig. 3 show two comparatively simple products which exemplify the wealth of opportunities which exist — a helical flower pot stand designed by a second year Loughborough student, Alison Bate, and a rain detector designed by a first year undergraduate, Suzanne Kettle.

Helical flower pot stand

The consideration of the stability of static forms is not as elementary an exercise as many might imagine and requires considerable clarity of thought. There are really three clear phases:

(i) the determination of critical loadings and disturbances i.e. how many flower pots should be considered to be in position and in which direction would an applied force have the most unsettling effect.

(ii) the estimation of the magnitude of the critical disturbing force necessary to overcome the restraints and the investigation of the events which might occur following the disturbance from equilibrium of the proposed design i.e. if 'tipped' would it topple?

(iii) feedback to the design process.

Considering critical loadings requires the analysis of the movements of the centre of gravity. If flower pots are added above the original centre of gravity then it will move upwards and similarly if flower pots are added below it will move downwards. In whatever position the flower pots are added the magnitude of the force at a given height necessary to cause toppling will increase assuming all of the weights are acting within the base area, but the angle at which toppling occurs will be dependent on the position of the centre of gravity.

When fully loaded the stand might be harder to move initially, but more likely to topple once movement has started and it will cause more damage. The stand will clearly be most likely to topple when the centre of gravity is at its highest i.e. when some of the upper pots have been added (working out how many is not straight forward) but easiest to move initially when empty. Fig. 4 illustrates the problem of the centre of gravity and Fig. 5 the location of the forces.

Estimating the magnitude of the disturbing force necessary to overcome the restraints imposed by the weights rests on the idea of taking moments and it is easily estimated that a force of

30-50N at a height of one metre would cause rotation, and that the angle at which toppling will occur is between 20° and 40° depending on the loading. The problems for the designer are choosing a reasonable value for the height of the force — the shoulder height of a ten-year old? — the magnitude of the force — the dynamic or static loads imposed by a ten-year old? — and deciding what an acceptable magnitude of the force is. The stand is clearly going to topple some time, but with product liability and no British Standards to fall back on the designers must make rational and responsible decisions.

Feedback to the design process from such decision-making can take a variety

of forms. If the designer has estimated a force of around 30N and a toppling angle of 20° and is in doubt there are many possible approaches to finding a solution:

- the base may be loaded with a heavy mass. This strategy has the advantage of maintaining the aesthetic form if the mass is concealed beneath the base, but the obvious disadvantage of making the stand heavy, with the associated transport and safety problems.

- the base diameter could be increased or the overall height reduced, but compromises would then need to be made concerning the aesthetic form of the product.

- holes could be provided instead of platforms for the pots, to prevent large pots being put towards the top of the stand.

- the 'beams' supporting the pots could be designed to deflect markedly if subjected to a force of more than, say, 10N, thus providing a visual warning of danger.

There are no doubt other possibilities, but the designer could only reach an acceptable solution by resolving the potentially conflicting pressures between aesthetic form, stability, safety and product abuse.

Rain detector

The rain detector — designed to hang on a washing line and give an audible warning — becomes really interesting from a mechanics viewpoint when the problem of getting it to clip over the line is considered. The interaction of the constraints imposed by the mechanical properties of plastics, manufacturing requirements and performance create a very significant pressure on the product form for the designer to resolve. In this case performance is represented by the achievement of sufficient deflection to clear the line with a comparatively small applied force and significant resistance to fatigue failure. Fig. 6 shows the desired layout of the product.

Polypropylene is really the best material because it has a good memory and resistance to creep and can be easily injection moulded. The difficulties arise because it is comparatively stiff in comparison to say polythene and nylon. There is also a further complication in that this section of the product must

FIG. 4 Effect of loading the stand

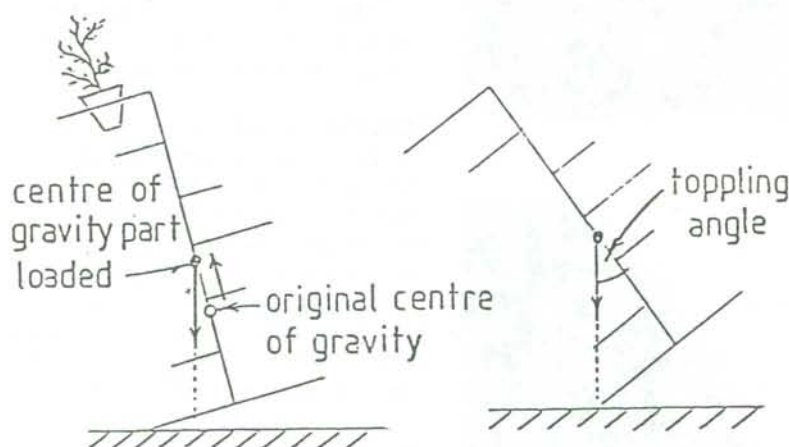
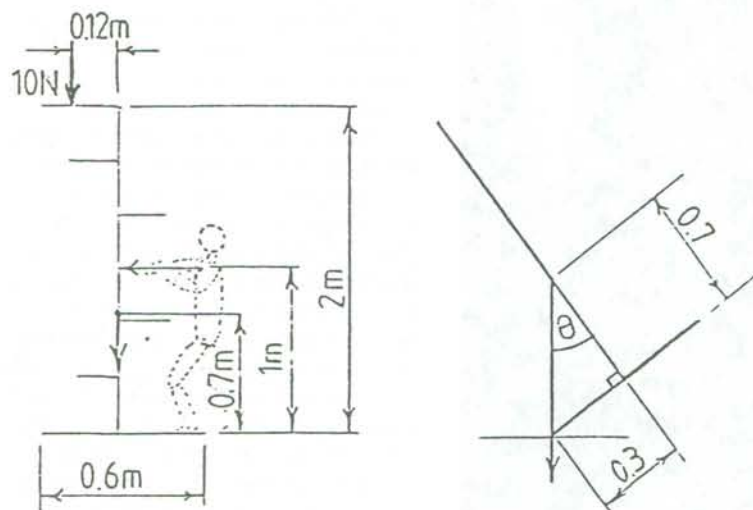


FIG. 5 Calculating the disturbing force and toppling angle



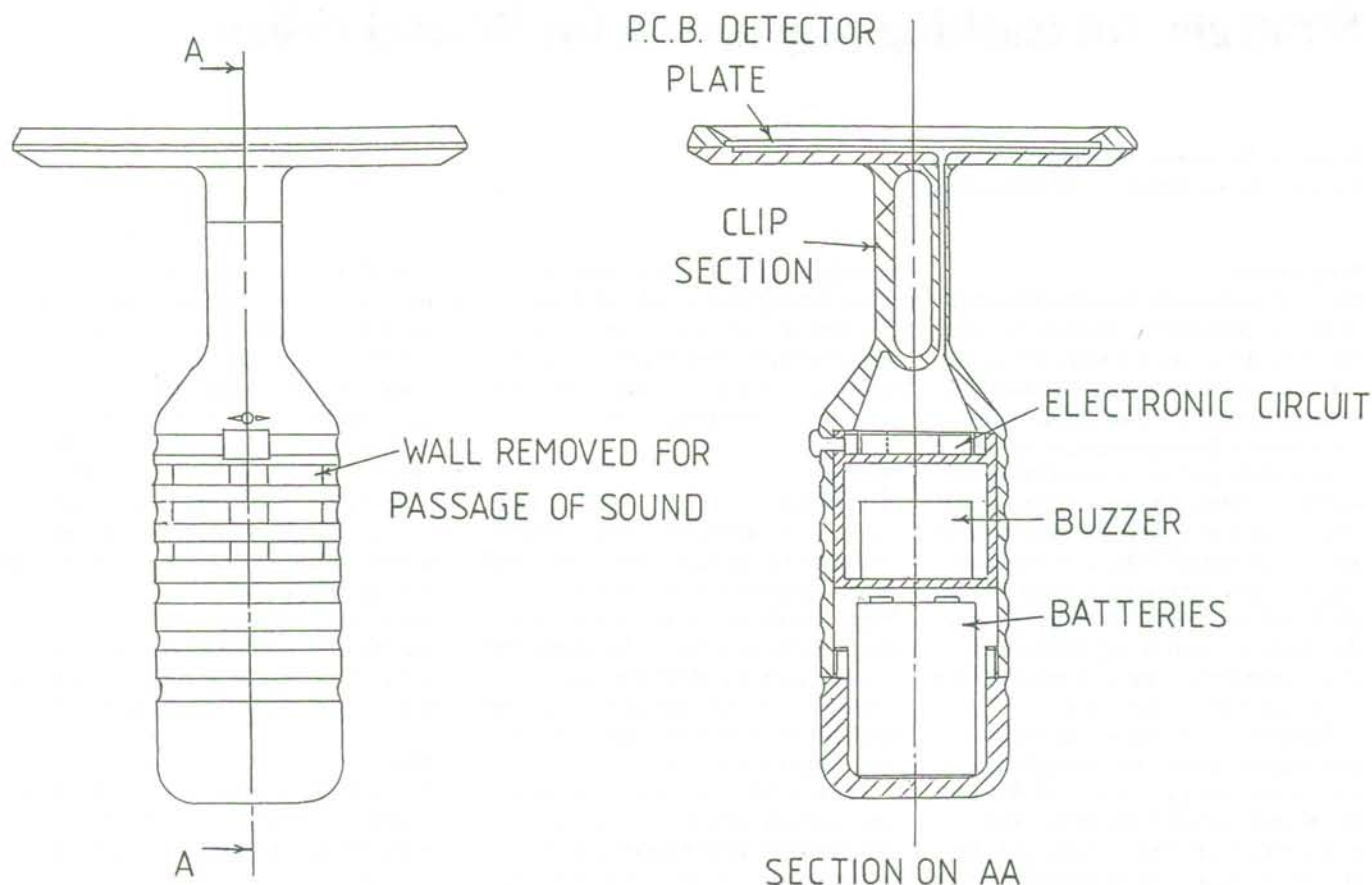


FIG. 6 Layout of the rain detector

carry the wires from the detector to the electronics and the sections must therefore be hollow further increasing the stiffness. Calculation will show that it is extremely difficult to get the required deflection with a 'beam' length of less than about 40mm and this constraint influences the entire form and aesthetics of the product. Incidentally to arrive at such a conclusion experimentally would take many hours whereas applying very well known mechanics allows this position to be reached in minutes.

Concluding Remarks

There is no doubt in my mind that Design and Technology with an emphasis on product design provides a very demanding and challenging subject area at any level of education if approached rigourously. A pseudo-scientific image in the end will be self-defeating and the forces trying to move the subject area in this direction should be resisted, along with those die-hard 'industrial designers' trying to avoid technology at all costs and those engineers who concentrate solely on performance and leave the generation of fully integrated products to someone else. Mechanics, along with all the other technological disciplines, has a vital role

to play and must not be allowed to be reduced to structures and mechanisms modules and construction kits. Designers must call up the necessary concepts in order to inform their decision making and there can be little doubt that the advent of powerful computer databases and modelling techniques will facilitate this process.

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