DESIGN TENSIONS

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SUMMARY

This paper reviews issues which must be resolved for any Engineering Design syllabus. The true value of design education can be judged by what a person retains after forgetting what was taught. By this criterion, the habits of thought, discipline and methods of tackling problems are more valuable than information. Several choices must be made between what is fashionable and what is desirable for design excellence, and are called "tensions".

OBJECTIVES

Eight tensions and corresponding recommendations are made for a design syllabus. Five further recommendations are made for achieving these goals.

METHOD

Engineering technology vs. engineering science: involves the concept of Information Half Life (IHL): the time in which half of what is learned is out of date. Priority should be given to material which has a longer IHL - engineering science.

Design vs. Analysis: Engineering courses tend to be analytical, but it is the design components which use these tools to synthesise something functional. More emphasis should be given to design in engineering courses.

System vs. component: Despite necessity, especially on large projects, to compartmentalise and fragment the scope, designers should maintain an overall (or global) view.

Interrelationships vs. rules of thumb: Rules of thumb are rarely discussed in most design courses and are regarded as inferior. Despite this, they are indispensable. Some rules of thumb have now become so entrenched that they are regarded as laws of nature.

Cost vs. elegance: The cost of manufacturing technique often determine the final design. Value analysis (itemised cost by scope requirements) will require knowledge of absolute limits.

Practical vs. theoretical: The inexperienced will often unwittingly neglect the aspects which differentiate the problem from the trivial such as when a tin can or a cereal box are optimised.

Computer literacy vs. numeracy: Never calculate anything unless you already know the approximate result. An error will then be recognised when it occurs.

CONCLUSION

Recommendations are made to foster good design and designers including team composition, management selection, advancement structures, responsibilities, and a variety

SUMMARY

This paper reviews issues which must be resolved for any Engineering Design syllabus. These include: engineering technology vs. engineering science, design vs. analysis, system vs. component, inter-relationships vs. rules of thumb, cost vs. elegance, capital vs. value, practical vs. theoretical, computer literacy vs. numeracy. Each issue is defined and illustrated with examples and recommendations for an Engineering Design syllabus. Further suggestions are made to foster good design and designers including team composition, management selection, advancement structures, responsibilities and variety of environments.

INTRODUCTION

The true value of design education can be judged by what a person retains after forgetting what was taught. By this criterion, the habits of thought, discipline and methods of tackling problems are more valuable than information (i.e. facts) which is easily forgotten. Put another way, if education emphasises information, then students, when they become practitioners, will only ever reflect others' thoughts, and continue to do things the same way - getting the same results: innovation is stifled. By contrast, if students are encouraged to evaluate novel ideas with timeless, general principles, innovation is more likely.

No strict definition of design is attempted here. It is a concept as slippery as creativity and innovation. We only pause to note that design is a uniquely human activity - a product of disciplined intelligence which results in something functional or aesthetically pleasing. Here we concentrate on functional (engineering) design which can include a range of activities from simple design with well established technology (implementation) rules, to designs whose innovative and novel content is sufficient to warrant a patent, i.e., an invention.

With this background, several choices must be made about what should be included in a design syllabus and what should not. Since these choices must be made between what is fashionable and what is desirable for design excellence, they have been labelled "tensions".

ENGINEERING TECHNOLOGY vs. ENGINEERING SCIENCE

Choosing between engineering technology and engineering science in the syllabus involves the concept of Information Half Life (IHL): the time in which half of what is learned is out of date. Since engineering technology is the application to hardware of engineering science then the IHL of engineering technology is much less than engineering science.

In some fields (eg computing) the IHL is less than three years: this means that during a four year course, the majority of the information learned in first year is out of date by graduation. For example, finite element analysis (FEA) has become a popular tool which some universities teach by requiring student proficiency in some package. Such a skill will have limited value because, even in the unlikely event that an employer uses the same package, the software will have been updated once or twice. In any case it is more useful (has a greater IHL) if the student becomes versed in the underlying mathematics and understands the limitations of the method. This will be valuable no matter what package is used.

Despite this, there is a tendency in many institutions to emphasise engineering technology over engineering science; the "applied" at the expense of the "pure"; vocationally specific rather than general training. The reason is not difficult to find - technology trained graduates are more immediately useful to employers than engineering science graduates. However, there are several disadvantages of such technology graduates:

(a) Their IHL is shorter - they reach their "use-by" date more rapidly,

(b) Their training is more specific - they accommodate change and innovation less,

(c) Increasingly specific graduate demands require a greater diversity in training.

Ironically, this defies the trend by many students to select more general courses such as engineering/arts, engineering/ economics, etc.

However, the training institutions cannot be held solely responsible for the trend toward engineering technology over engineering science - they are responding to Industry demands. Industry tends to take short-term views and often does not wish to spend the time and money waiting for graduates to become useful. It should not then complain when its staff experience trouble adapting to new trading conditions.

This is not to suggest that we should only train engineering science graduates. On the contrary, we need more technologists than engineering science graduates. However, the short term focus of both industry and universities needs to be balanced with longer views.

Further, the originality and innovation necessary for design requires the most broadly trained people.

DESIGN vs. ANALYSIS

Engineering courses, by nature and necessity tend to be analytical. It is the design components which use these tools to synthesise something functional because something more than the comparatively routine art of analysis is required for design. The extra ingredients for design include judgement about which, often, little is quantifiable. This makes teaching such design subjects demanding and frustrating especially when students request ritualised procedures with guaranteed outcomes.

This only partly explains why so little space is given to design in engineering courses. One need only compare the number of design professorships with those in (say) soil mechanics and thermodynamics to realise how little design is taught. This anomaly is made more profound by the fact that design, as opposed to analysis, is one of the distinguishing features of engineering as opposed to science.

Again, universities cannot be held solely responsible for so little emphasis on design. Most industry similarly encourages capable design engineers out of their craft into management by making it the only path to advancement. Such companies clearly place a low value on good design and its practitioners.

SYSTEM vs. COMPONENT

It has become a practical necessity, especially on large projects, to compartmentalise and fragment the scope to make it manageable. A danger occurs when a lone designer optimises a component without regard to the larger system objectives. That is, no matter what the job, an overall (or global) view should prevail.

To illustrate this tension, consider the design of a solar water heater and the problem of selecting the water channel dimensions in the absorber plate. To maximise the heat transfer, the absorber plate channels should be kept small. However, when coupled to a storage tank with natural convection driving the circulation, these water channels must be larger, but not too large, or heat transfer and temperature difference across the plate are too small. Similarly, of the channels are too small, the flow is restricted giving poor results. There is an optimum channel dimension which can be calculated based on system, rather than component, characteristics.

This tension underlines the importance of mathematical modelling - a practice which examines all system parameters simultaneously.

INTERRELATIONSHIPS vs. RULES OF THUMB

There are a number of system characteristics (interrelationships between the components and their behaviour) which are either so complex or poorly understood or of minor consequence that it has become necessary to use established, empirical rules of thumb. A few are listed below. For reasons which are not obvious (at least to me) such rules of thumb are rarely discussed in most design courses and are even regarded as second class citizens. Despite this, they are indispensable. Some rules of thumb include:

* 'O' ring diameter d (mm) for a seal of diameter D (mm): d j ¼/D

* Pipe wall thickness T (mm) for a carbon steel pipe of diameter D (mm): T j ½ /D

* Reaction time between a major plant disaster and remedial action is about 15 minutes

* Minimum bolt size on a petrochemical plant is 16 mm

* Design velocity of liquid in pipelines is between 2 - 4 m/s

* Manufacturing and assembly tolerances

Other rules of thumb have now become so entrenched that they are regarded as laws of nature. For example, the polytropic compression "laws" are merely fancy rules of thumb! [Such pseudo-laws are part of the important difference between engineering and science. Engineering can use such laws without understanding the fundamental physical processes while science exists to offer explanations for, and catalogue such phenomena. Therefore such rules of thumb have no place in science but are a fertile area for its investigation.]

Every branch of engineering has numerous rules of thumb and young engineers should be encouraged to collect them without being slave to them. Especially useful are rules of thumb which correlate cost consequences - see below. Unfortunately, such data usually has a half life of two years or less. This is another example of the need for constant experience.

COST vs. ELEGANCE

It is one of the conspicuous characteristics of inexperience that elegance is preferred over cost. For example, consider the design of a pressure storage system for 780 m^3 at 1.2 MPa in carbon steel with no corrosion allowance. Two options are (1) a single sphere 11.45 m diameter, 20 mm thick, or, (2) two horizontal cylinders, 4 m diameter, 30 m long, 14 mm thick. The novice might immediately select the sphere because it uses 65 tonnes of steel while the cylinders use 91 tonnes - 40% more than the sphere! Despite this, the experienced designer will select the cylinders because they will be about half the cost of the sphere for a series of reasons including more automated, shop fabrication.

Notice that in this example, the manufacturing technique and its costs were the determining factor - such considerations are given scant attention in design courses. Of course, there will be occasions where the requirements of aesthetics (visual or simply cerebral) need to prevail over functionality. In such circumstances elegance will usually be given priority over cost.

VALUE vs. CAPITAL

By careful analysis it is possible to break the total cost down, not by the system components, but by scope requirements. Such a value analysis is used to decide which requirements can be relaxed to reduce cost.

For example, consider a stirred vertical reactor 2.0 m diameter, design pressure 2.0 MPa. Further, it is desirable to be able to drain the vessel completely using a previously selected valve which can be no closer than 700 mm from the centre of the vessel because of the bottom entry agitator. This last requirement necessitates a large (1.5 m diameter) forging, 200 mm thick with an elaborately machined upper surface. Therefore the fully draining requirement costs about $40,000 - more than the valve in question! If a new valve is purchased, substantial cost saving would result.

Such value analysis will often require knowledge of some absolute limits beyond which it is impossible to improve. Some of these are familiar:

* Carnot efficiency of heat engines

* Nyquist sampling frequency

* Minimum volume V_m, of metal of design strength f, required to contain a volume of V_c at pressure P, is: $V_m = 3V_cP/2f$, for a sphere, and

$V_m = 2V_cP(l+0.7)/(l+0.333)f$, for a cylinder with l = length/diameter

Many more examples could be given. Again, engineers should be encouraged to collect such data and more should be included in undergraduate courses.

PRACTICAL vs. THEORETICAL

It is well known that a cylinder of given volume has minimum surface area when the length is equal to the diameter. The reason canned pet food and fruit etc, in 400 mL steel cans (the largest population) do not adopt this theoretical optimum is simple: it ignores the fact that a steel can must have a top and bottom rim. Such rims have five thicknesses of folded steel plate and are typically 3 mm high. When this material is included in the analysis, optimum can proportions arise which are very similar to those commonly used. Similarly, a rectangular prism (box) of given volume has a minimum surface area when it is a cube. But when breakfast cereal packets and other such cartons are optimised around the need to provide glue tabs and flaps, available cereal packets are close to optimum proportions.

These examples illustrate the hazards of making seemingly harmless simplifying assumptions in order to abstract the problem at hand. The inexperienced will often unwittingly neglect the aspects which differentiate the problem from the trivial. Hence they approximate the problem away - an advanced and subtle form of denial.

COMPUTER LITERACY vs. NUMERACY

Engineers were once the most numerate people - they knew the approximate magnitude of all kinds of things. Since the arrival of cheap computing facilities (both hand held and desk-top), modern engineers are sometimes more inclined to calculate than estimate. This would be bad enough except that most go on to believe the result regardless of what assumptions and erroneous keystrokes produced it. This illustrates a serious short-coming of fancy graphical computers - they make convincing liars, especially for the gullible and innumerate.

Before hand-held calculators, nomograms were used to calculate quite diverse things; they had the advantage of providing a "feel" for not only the magnitudes but their sensitivity to input parameters. Such graphical techniques are now regarded as inferior and their use has all but disappeared - a pity! I encourage the maxim: never calculate anything unless you already know the approximate result. An error will then be recognised when it occurs. Put another way, digital computing is only to calculate the second and third significant figures - not the first. Engineers should rely on an educated "feel" which obviously takes time and experience to develop.

For these reasons Appendix B was added to AS 1210 - SAA Pressure Vessel Code to stem the tide of humbug disguised as pretty pictures painted by finite element packages in the name of fundamental stress analysis. Many had irrelevant boundary conditions, erroneous displacements and otherwise misleading results. The Appendix B now contains a check list to help prevent this.

CREATING A DESIGN-CONDUCIVE ENVIRONMENT

It is my observation that good designers grow by osmosis rather than being trained in the skill. That is, the discipline of design is caught rather than taught. It is therefore essential that aspiring designers (of which there are too few) are given plenty of opportunity to ply their craft, both at university and in industry, by being apprenticed to more experienced engineers. A number of proposals are listed below which may help grow and retain good design engineers.

1. Responsibility

It is a simple law of human development that people grow into their surroundings. If designers are never asked to do great designs they never will. (Whether they are able is another matter.) Some managers lament the fact that design training by osmosis takes too long. In some cases it is their own fault - their own conservatism prevents young engineers having responsibility to develop their craft. The quickest way to learn to swim is to be thrown in the deep end with an experienced swimmer near by.

2. New Environment

Just as necessity is the great stimulus for design creativity, so new surroundings can prod people to look at life (and designs) in a fresh way. A new environment can stimulate connections between (previously) unconnected things, or at least, alert designers to new ways of doing something. The current trend to have students spend six months or a year before graduation in an industrial environment should be encouraged.

To this end, it would be desirable for university design lecturers to spend time in industry and vice versa, eg, by staff swaps. Designers should be encouraged to work in a variety of fields where practical - cross fertilisation of fields is often productive.

3. Team Composition

Design engineers can be grouped into three classes: the naive or inexperienced; the mature who can grasp design complexity; and the immature - experienced designers who never matured. This last group is dangerous in a design team because they poison new ideas - they specialise in expressing reasons why a novel idea will not work.

It is therefore useful and healthy to mix developing and mature design engineers who stimulate and learn from each other. However, immature designers should be removed and placed elsewhere. It is a salient lesson of history that many of the great developments were delayed or passed to others because of such immature people. For example the personal computer, moveable type printing, flight recorder "black box", etc.

4. Management

It is a law of teams that the character and style of leadership influences that of the whole team which underlines the importance of competent, supportive management. Occasionally, immature people are (foolishly) required to manage design teams. The effects are insidious: mild rewards for success and "public crucifixions" for even minor failures. All design involves risk. Therefore some failures are inevitable and must be managed with suitable contingencies. Such contingencies include larger safety factors, fail-safe designs, fall-back options, insurance, development trials, etc.

Immature management should not be tolerated. Creativity needs a supportive environment where people feel free to express ideas without fear of failure or denigration. Severe cost constraints can breed immature managers who promote the view that such behaviour is supported by senior management policy.

5. Advancement

It is often forgotten that designers are human and so are ambitious. If a company is structured so that the only possible path to advancement (more pay and recognition) is into management, then two clear signals are given to young designers: your design work is not highly valued here, and, get out of design as quickly as possible. Many are then curious why there are not more mature designers.

While immature management is becoming less common, some are simply changing tack to produce discouraging organisation structures for all except managers. However, some modern companies now provide at least two career ladders: one technical and the other managerial which helps stem the brain drain from technical disciplines.

CONCLUSION

The above list of design tensions and recommendations is not exhaustive and is intended to provoke thoughtful discussion. It is hoped that both industry and universities will take a longer term view of graduates to develop professional, mature design engineers able to adapt and innovate**.**