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A Course in Statistical Engineering*

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A course in statistical engineering has recently been added to the Ford Motor Company's Technical Education Program. The aim was to produce materials suitable for use by Ford but which could also be promoted by the UK's Royal Statistical Society within the university sector. The course is built around a sequence of realistic tasks dictated by the flow of the product creation process. Its structure and content is thus driven by engineering need rather than statistical method, promoting constructivist learning. Before describing the course content we review the changing role of the engineer and comment on the relationships between Systems Engineering, Design for Six Sigma and Statistical Engineering. We give details of a case study which plays a crucial role in the course. We focus on some important features of the development process and conclude with a discussion of the approach we have taken and possible future developments.

INTRODUCTION

THE FORD TECHNICAL EDUCATION PROGRAM (FTEP) is the corporate training programme that covers the fundamental tools required by engineers as a part of the engineering process. FTEP originated in the mid-1990s as part of a globalisation initiative within Ford Motor Company, and is directed at the graduate technical workforce worldwide. Each of the FTEP courses is subject to regular review and both the individual courses and the overall curriculum are updated in line with developments to the engineering process. A course in statistical engineering has recently been added to the FTEP curriculum and forms the subject of this paper.

The course is, we believe, very innovative in its structure and much of its content. The objective of the paper is to describe the thinking behind the course, to explain its unusual structure, to review the course materials and to discuss the approach that we have taken in developing these materials.

While the concept of statistical engineering has been promoted within Ford since the early 1990s, notably by Tim Davis, it was Richard Parry-Jones (Group Vice President, Product Development and Quality) in his 1999 Engineering Manufacturing lecture to the UK Royal Academy of Engineering who prompted the development of the course (Parry-Jones [1]). The lecture advocated the use of statistical engineering to manage the effects of variation on the performance of engineered systems. Parry-Jones defined statistical engineering as 'the combination of engineering science (the study of physics and materials) and statistical science (the empirical modelling of variability)'.

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Since statistical engineering and the other techniques covered within FTEP are all standard methods that enhance the engineering process it might be expected that engineering graduates would first meet these techniques as part of their undergraduate studies. It is Ford's experience, however, that it is very unusual for engineering graduates to have knowledge of all of the methods covered by FTEP and, even where this is the case, individual competency is often not sufficient to allow the methods to be applied effectively within the product creation process. This point was recognised by Parry-Jones (Parry-Jones [1]) who asked that 'the use of statistical engineering methods be taught and embedded in the undergraduate curricula'.

The important points made by Parry-Jones were taken up enthusiastically by members of some of the UK professional institutions, and the origin of the statistical engineering course was at a meeting jointly organised by the Institute of Electrical Engineers Quality Management Committee and the Royal Statistical Society (RSS) Quality Improvement Committee. During discussion of how the Parry-Jones points would be best addressed, Tim Nicholls of Ford proposed that the company develop a training course in conjunction with the Royal Statistical Society and that the RSS promote the use of the course materials within the UK university sector with the aim of improving the teaching of statistics in engineering curricula.

In the next two sections we explain the training philosophy that underpins the course and review the engineering context in which it was developed. We then describe the course content, including a substantial case study. The paper ends with a discussion of the approach we have taken and possible future developments.

PHILOSOPHY OF THE COURSE

The importance of relating the content of training to the learner's environment and intellectual needs has long been recognised (Dewey [2]), and this insight was crucial to the development, within Ford of Europe, of the Engineering Quality Improvement Programme (EQUIP) in the late 1980s (Combes *et al.* [3]). The EQUIP programme was later merged with similar North American training programmes to form FTEP.

Within EQUIP and FTEP the overall *product creation process* is taken to represent the learner's environment. The product creation process is shown as a cycle of activities in Fig. 1 (adapted from Grove and Nicholls [4]). The word 'cycle' is used to acknowledge the fact that very few products are created without reference to the experience gained in designing and manufacturing a preceding, probably similar, product. For activities that relate primarily to product design the labels are placed outside the circle; activities that relate primarily to the product's manufacturing process are placed inside. We have not attempted to indicate the duration of each activity and we recognise that, in the spirit of concurrent engineering, some activities take place simultaneously.

One of the key design criteria for the statistical engineering course was that it was driven by engineering need rather than statistical method since this would promote constructivist learning, that is allow the learner to relate the training content to their own experience and construct knowledge for themselves (Honebein *et al.* [5]). The high level engineering needs considered in the course relate largely to issues concerned with product design and manufacture.

In fact, the statistical engineering course has extended the philosophical approach of EQUIP and FTEP by setting the course content in a sequence of realistic engineering tasks dictated by the flow of the product creation process. Each task is associated with one or more engineering deliverables, and the concepts and skills needed to achieve the deliverables largely determined the sequence in which the statistical methods are introduced in the course. In appreciating this point it is important to distinguish the approach of teaching statistics as an integral part of the engineering process from the more traditional course which uses engineering examples only as illustrations. The difference between these two approaches is that, in the former, statistical techniques are used to achieve engineering deliverables while in the latter the primary function of the examples is to reinforce the learning of statistical concepts and techniques. This is not to say that learning reinforcement is not important, but this can easily be accommodated through the former approach.

THE ENGINEERING CONTEXT

Oh [6] summarised the changes that occurred in the 'Quality Movement' between the 1940s and mid-1990s, driven by intensified competition and technological advance. The trends that he identified have accelerated since the time of his article, and in this section we discuss some issues that are particularly relevant to the statistical engineering course.

The introduction and rapid advance of new technologies has a direct implication, both quantitative and qualitative, for the engineers' workload. As Oh suggested, with rapid technological advance experience becomes less relevant. This, combined with an increasing workload, renders impractical the traditional strategy of design-test-fix (Campean

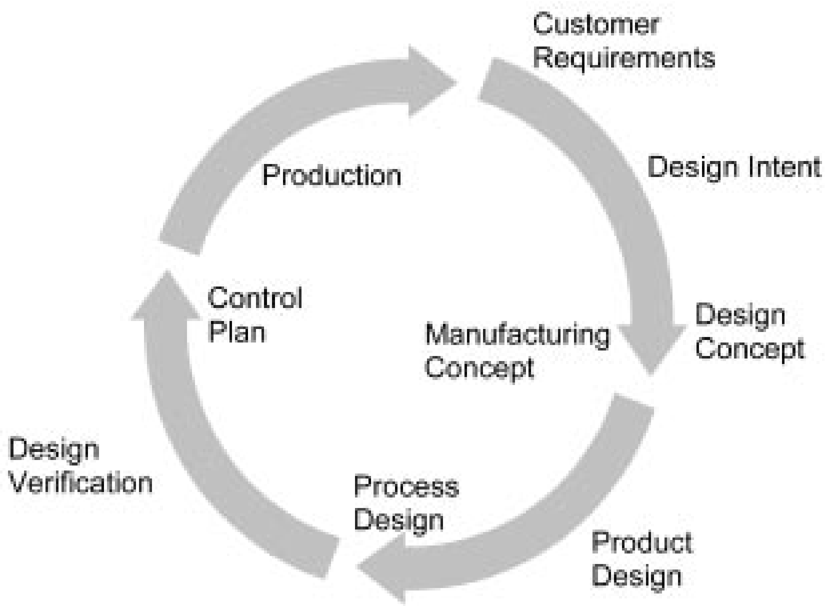

Fig. 1. Product creation process.

and Brunson [7]). Engineers are under pressure to change their approach from one of *assessment* that takes place downstream to one of *anticipation* that occurs early in the design process.

Another implication of technological advance is increased complexity. Managing complexity becomes the critical task, and the role of many engineers has changed accordingly from component designer to systems integrator. Systems engineering is now one of the skills expected from any automotive engineer.

The need to manage complexity by addressing issues upstream changes the way engineers use some of the traditional quality engineering tools, including FMEA, QFD, robustness and reliability methods. Whereas ten years ago these tools were used in isolation and usually to solve a specific problem, they are often used now in integration and proactively to address the issue of complexity by managing interfaces. A recent study (Webb [8]) into the application of reliability and robustness tools to the design process has shown that 'ordinary' engineers are more positive about the effectiveness of the quality tools than quality practitioners themselves. This suggests that quality tools are now regarded as engineering disciplines and are an integral part of the engineering process.

The increased use of analytical modelling tools is an enabler for focussing on ideal function, in other words for seeking ideal performance rather than simply trying to avoid failure. Through understanding and modelling the effects of variation early in the design process, design configurations and settings optimal from a reliability and robustness point of view can be specified. This is, as Oh [6] pointed out, a much more efficient strategy than design-test-fix.

Golomski [9] summarised the changes in quality focus and strategy as a shift from 'getting things right' to 'doing the right things'. Managing interfaces through integrated use of quality tools, focussing on ideal function and building virtual models to perform assessments early in the design process are part of 'doing the right things', paving the way for sustained productivity improvement. There is also a need for a change in the mindset of the design engineer. With the decreased relevance of experience, additional skills are required to allow the engineer to perform at the expected level. In particular, understanding and modelling the effects of variation and uncertainty is a key skill needed in the upstream part of the design process. Statistical tools and methods are thus becoming an integral part of engineering, justifying the training in statistical engineering demanded by Parry-Jones [1].

As we suggested above, one major feature of the changing role of the engineer is the move from component design to system integration. System optimisation is achieved through the management of the interfaces between the component parts of a system, and interface management with a complex product like a vehicle requires a systematic and structured approach. One such structured approach is that used in Ford which can be represented by the systems engineering 'V model' shown on the left-hand side of Fig. 2.

In using the V model, vehicle-level customer needs and wants are cascaded down from vehicle to component through the relevant subsystems. The left-hand side of the V represents this top-down requirements cascade, which drives product design. Once designed, the integration of components into subsystems and subsystems into the vehicle is verified in a bottom up process as depicted on the right-hand side of the V. The high level nature of the V model means that it needs to be supported by a set of pragmatic engineering approaches or tools if it is to have direct relevance to an engineer's day-to-day tasks. One approach which can be used within the framework of systems engineering is Design for Six Sigma (DfSS). Ford applies DfSS as a four phase process: Design, Characterise, Optimise and Verify (DCOV), which is shown mapped onto the V on the right-hand side of Fig. 2. Further details of the DCOV process are given in Hu *et al.* [10].

We see statistical engineering as integral to the application of DfSS. The development of transfer function (response surface) models and their use in managing interfaces and in design optimisation is core to DfSS. In the DCOV process, transfer functions provide the link between the requirements cascade in the Define phase and the product design established within the Characterise phase. Transfer functions are then used for design optimisation in Optimise. In DfSS, transfer functions may be deduced from physical knowledge of the

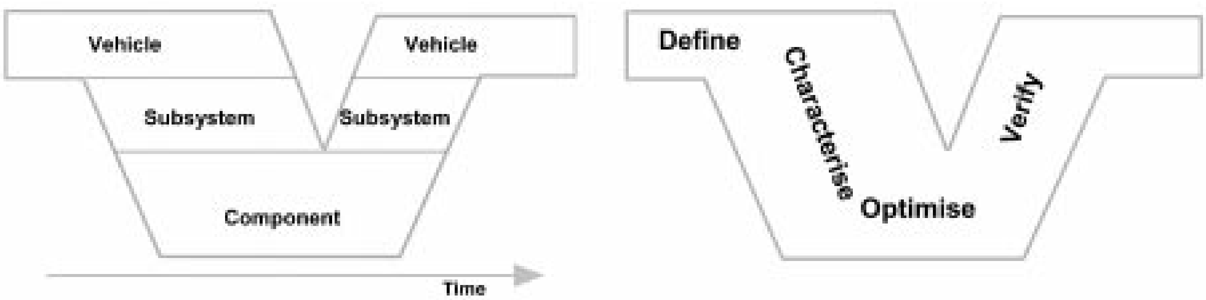

Fig. 2. Systems Engineering V model and DCOV

science or geometry of a system, or estimated empirically by applying regression methods to data. In teaching statistical engineering it is natural to emphasise the empirical development of transfer functions, but we shall suggest in section 4 that the task based approach we have adopted would provide a suitable framework for demonstrating the interplay between deduction from physical knowledge and induction from data.

THE COURSE MATERIALS

As we described in the Introduction, the course is constructed around a sequence of realistic engineering tasks drawn from the product creation process. This structure conforms to the model of problem based learning (Savery and Duffy [11]). The cyclical nature of the product creation process offered a number of possible starting points for the course, and we decided to 'break into' the cycle at the stage where a design specification exists (including target values for key engineering metrics, and associated tolerances) together with a design concept thought to be capable of achieving the targets.

Having identified a sequence of engineering tasks, with associated deliverables, elements of the statistical content were introduced to support the achievement of the engineering deliverables, as shown in Table 1.

In addition to the eleven sections detailed in Table 1, there is a Section 12, which relates to the design of a new generation of product. From a

Table 1. Course structure—statistical content in support of engineering tasks

Section	Engineering deliverable(s)	Statistical content
1	A product design concept that can achieve the functional target	Least squares fitting (straight line and quadratic curve) Residuals Statistical model for x/y data, incorporating random variation
2	A robustness assessment of the design concept	Introduction to designed experiments Two-level orthogonal arrays Effect plots and sensitivity analysis
3	An objective measure of piece-to-piece variation for an existing similar product	Run charts Probability distributions The Normal distribution family, μ and σ Statistical model of stable process variation Normal probability plots Sample mean and standard deviation
4	A transfer function for the product An optimised product design and an assessment of its functional performance	Transfer functions represented by quadratic response surfaces Contour plots Three-level full factorial designs Fitting a response surface transfer function by least squares Coded factor levels Interaction and the shape of the surface Statistical models with two or more x-variables
5	An estimate of the useful life of the product	Life data modelling Weibull distribution family Weibull plots Estimation of survival probabilities and percentiles Precision of estimates Use of simulation to study the effect of sample size on precision
6	A list of the manufacturing process parameters that affect an important product characteristic	Location and dispersion effects Use of a two-level experiment to investigate location and dispersion effects Full and Half Normal plots of effects The link between regression analysis and effects analysis Confounding in small experiments
7	A first draft of the transfer function for the manufacturing process	Response surface experiments Standard response surface designs Optimal response surface designs (brief treatment) Standard errors of regression coefficients Lack of fit
8	A measurement system with acceptable performance	Repeatability and reproducibility Statistical models of measurement system output Additive properties of variances Sums of squares and degrees of freedom One-way ANOVA
9	A refined version of the transfer function for the manufacturing process	Residual plots Options for reacting to outliers Use of t-ratios and p-values to identify redundant terms
10	An on-target manufacturing process optimised in terms of cost	Functional optimization subject to constraints (informal treatment)
11	An acceptable level of variation in process parameters	Capability indices Statistical model of unstable process variation Special and common cause variation Shewhart control charts

statistical point of view this final section is intended to reinforce the learning acquired during the previous sections, and no new ideas are introduced.

The sequencing of the statistical content presented us with a challenge, as the engineering sequence dictated by the product creation process does not map conveniently onto the traditional sequence in which concepts and methods are introduced in an introductory course. However, we believe we have identified an effective sequence.

We assume no prior statistical knowledge apart from an understanding of, and ability to calculate, the arithmetic mean. An understanding of 'school' mathematics was also assumed such as the ability to distinguish between linear and quadratic equations. All the statistical ideas and methods are introduced by animated graphics or other diagrams, supported by a few carefully selected formulae. This facilitates the inclusion of topics which are usually thought of as too advanced for a relatively short introductory course, such as multiple regression (introduced in Section 4 of the course) and Weibull analysis (in Section 5).

Figure 3 maps out the content in a different way, showing how the statistical tools and concepts feed into the main areas of application of statistical engineering (gauge R&R, life data modelling, process control, experimentation, transfer functions and optimisation) which are shown in bold boxes, and hence contribute towards achieving the engineering deliverables (shown in shaded blocks).

Figure 3 shows, for example, that experimentation directly facilitates two engineering deliverables within the course, the identification of key factors affecting a manufacturing process and an assessment of the robustness of a design concept. It also indirectly facilitates design optimisation by supplying data to which transfer functions can be fitted prior to optimisation. Two-level and three-level experimental designs are both included. Analysis of two-level experiments is through response plots, normal and half-normal plots, and the latter methods are underpinned by an understanding of the normal distribution. The role of three-level experimental designs is explored by comparing, at a non-mathematical level, the merits of standard designs such as the central composite with those of computer-generated optimal designs.

We have used this map in follow-up sessions with engineers, aimed at promoting wider application of the methods covered in the course. The map, including the thumbnail graphics, serves to remind participants of the content, as a preliminary to a discussion of specific projects.

In this unusual approach to teaching statistics it is particularly important to maintain coherence. This is done by emphasising three recurring themes:

- the development (by regression) and use of transfer functions that link product outputs and product characteristics with process parameters;

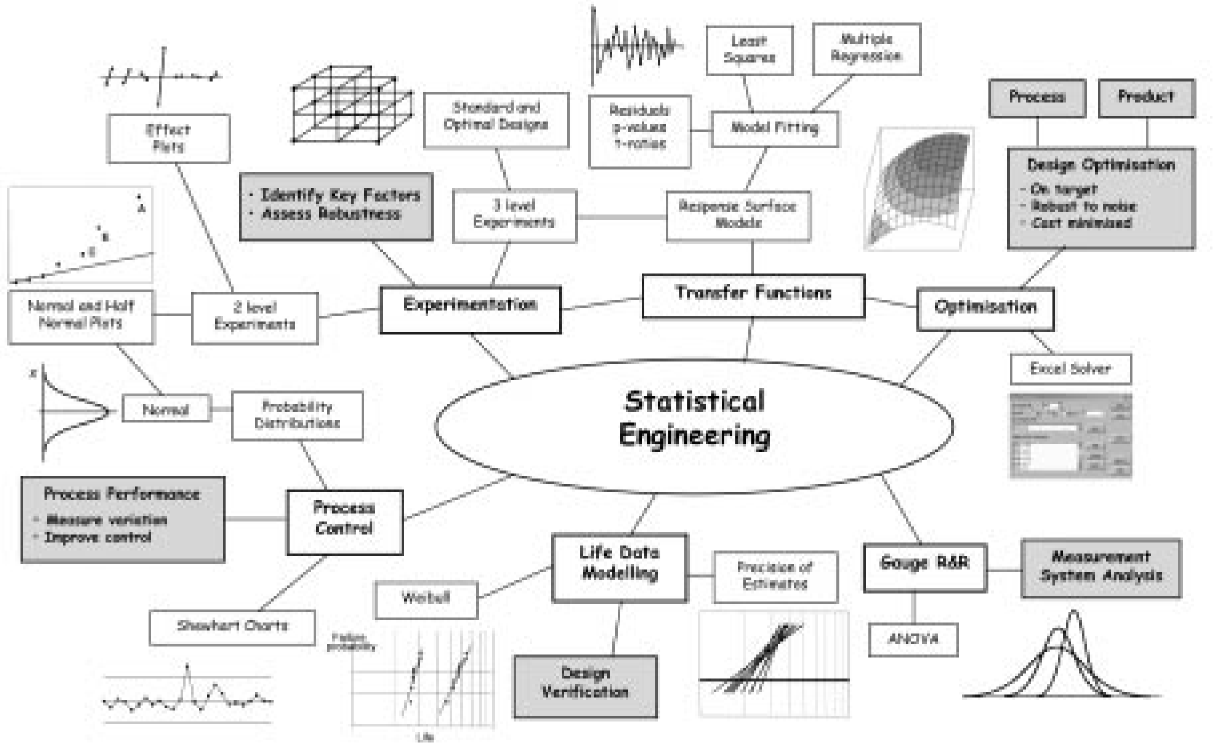

Fig. 3. Map of the course content

- the use of statistical models which incorporate probability distributions to describe random variation; these models are always defined pictorially, as for example in Fig. 4, which is our version of the formal model $y = f(x_1, x_2) + \varepsilon$, where ε is a random variable;
- the precision of statistical estimates and the relationships between precision, variability, sample size and available resources.

Since most of the statistical ideas and tools are relevant to several engineering tasks, they are first introduced very informally and then re-examined from an increasingly sophisticated point of view, motivated by questions which arise in the engineering context. For example, the importance of understanding the precision of a statistical estimate we will show how simulated Weibull samples can be used to quantify the likely variation in an estimated percentile of the life distribution, and hence guide the choice of sample size in life testing. Standard errors are defined and illustrated in the context of choosing the number of runs in a process experiment. These are used to calculate t-ratios for regression coefficients, with the objective of simplifying the estimated process transfer function. The reappearance of certain statistical ideas also provides an opportunity for reinforcement of earlier learning. For example, participants fit quadratic response surfaces to three different data sets.

CASE STUDY

In order to ensure that the engineering tasks were authentic and presented sufficient of an intellectual challenge to an engineer to allow meaningful constructivist learning (Gros [12]) a case study storyline was constructed based on tasks drawn from the design and manufacture of a real product. The case study flows through the entire course, which facilitates coherence between the different engineering tasks, a key feature of constructivist learning (Collins *et al.* [13]).

Recognising that the training materials were to be used both within and outside of Ford Motor Company, a simple 'everyday' automotive component was chosen as the basis of the case study. The component chosen was a fuel filler door (FFD), the flap mounted on the vehicle body that both protects and allows access to the fuel filler cap. This particular FFD is manually operated from outside the vehicle.

The specifications for the FFD are based on the requirements of the end customer and other sources, including legal requirements. During the course we focus on two customer requirements: the FFD must be easy to operate, and once opened, it must stay open unless manually closed. The engineering translation of the first requirement is that the effort required to operate the FFD must not exceed 18 N, and that the preferred (target) effort is 10.5 N. In relation to the second requirement, the specification states that the effort must not be less than 4.5 N; in this case the relevant effort is that required to start closing the flap. A design team proposed a concept in which fully opening the FFD involves forcing a pin, which is moulded as part of the door, through a narrow gap in a hinged stay. Once the FFD is fully opened, it will remain in that position until an effort is supplied sufficient to overcome the interference between the pin and the stay gap.

The stay and pin mechanism is shown in Fig. 5. The door (shown almost fully open) is hinged to another moulded part (the housing). The top of the pin is shown protruding through the stay.

The case study storyline mimics the journey of a design team around the product creation cycle for the FFD, unfolding as a succession of engineering tasks that mirror the progression of the course. Figure 6 is a graphical representation of the storyline. We use a spiral shape rather than a circle so that the beginning of the story (evaluation of the functionality of the design concept) and end (consideration of the next generation of FFD) are clear. The final task actually includes a second fairly brief tour of the complete cycle.

Accomplishing each task within the case study involves application of the statistical concepts and

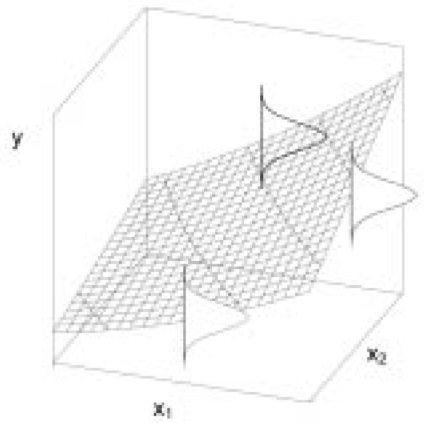

Fig. 4. Pictorial representation of the model $y = f(x_1, x_2) + \varepsilon$.

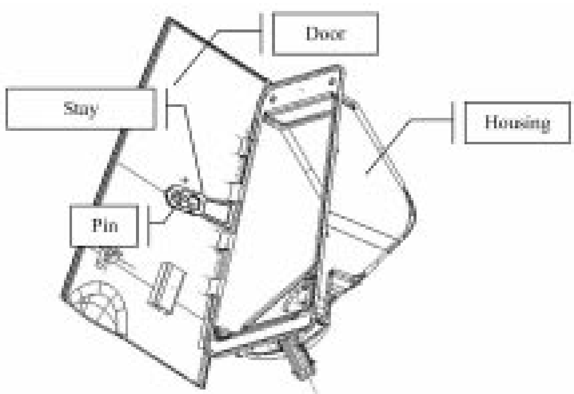

Fig. 5. Fuel filler door.

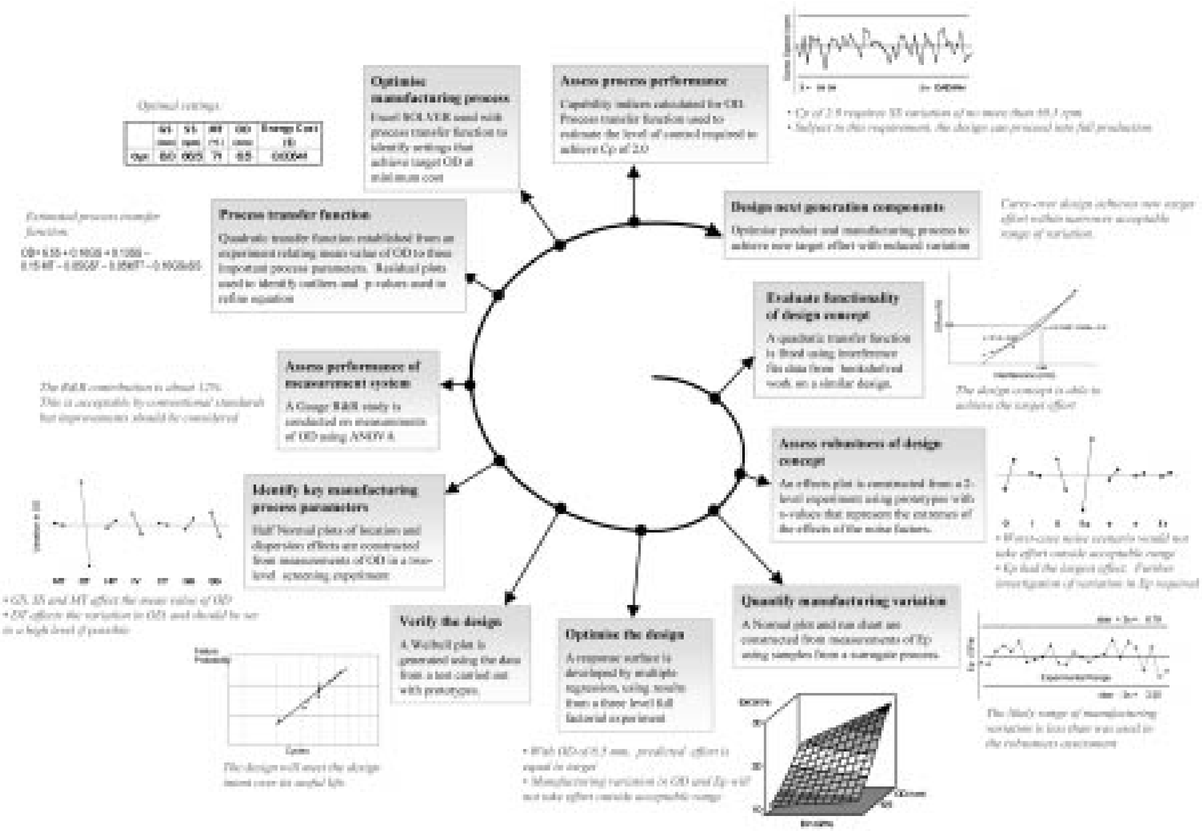

Fig. 6. Map of the FFD case study.

tools taught in the respective section, and Fig. 6 shows the objective of each task, an outline of the statistical content and a summary of the output, focusing on the engineering deliverable. In order to take maximum advantage of the problem-based learning context, the focus for each task is split between a statistical component (understanding and using correctly the statistical tools) and an engineering component (interpretation of the results). There is also a clear link between tasks, as the engineering context for each task builds upon the findings from the previous task.

Although the FFD is a part of the larger fuel system for a vehicle it is relatively self-contained. It was felt to be important that participants were able to relate the course content to other more complex components, subsystems and systems. In order to do this the case study materials relating to the FFD make use of the systems engineering V model. The design and manufacture of the FFD is thus seen as being an integral part of the design and manufacture of the vehicle fuel system and hence of the vehicle itself.

Diagrams similar to Fig. 7 are used repeatedly within the case study. Figure 7, which relates specifically to the Define and Characterise phases of DCOV, shows how a high-level customer requirement ('Easy to re-fuel', a 'Y' in conventional DfSS notation) flows down to a component-level requirement (opening effort, which is a 'y'). Opening effort depends on material properties and dimensions of the FFD ('x's') such as the outside diameter (OD) of the pin. In turn, the x-variables are influenced by manufacturing process parameters (which we call 'p's'), such as the screw speed of an injection moulding machine. There are case study exercises which estimate the relevant transfer functions and use them to explore the cascade of target values from y to x to p. There are also exercises which reverse the process and study the effect of variation in process parameters ('Δp') on pin OD ('Δx') and hence on opening effort ('Δy').

COURSE DEVELOPMENT

The purpose of this section is not to give a 'blow by blow' account of course development, but rather to focus on a few important features of the process.

Prior to the launch of the course it was piloted in a three-day format within Ford, in Germany, the UK and the USA. The pilot audiences for the course in the UK included graduate engineers from within the company (the target audience in Ford) and undergraduates from the University of Greenwich. In Germany and the USA the pilot audiences included both graduate engineers and a number of statistical specialists from within Ford. The course materials were also tried out at the Universities of Bradford and Southampton, in a

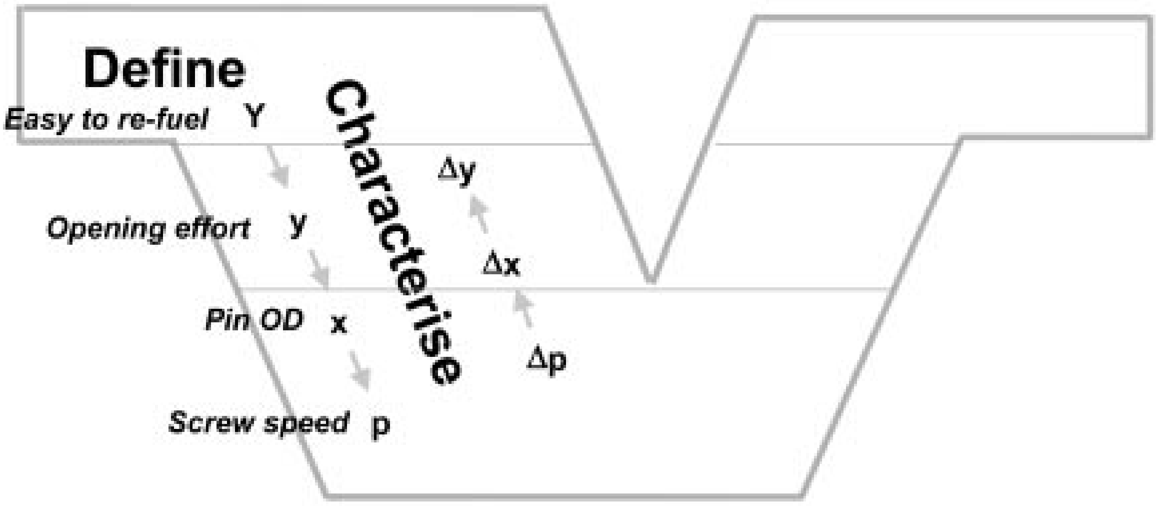

Fig. 7. The fuel filler door in the context of systems engineering.

conventional one-semester lecture/tutorial form, with full-time M.Sc. and M.Eng. students.

The materials were reviewed by two external experts, Dr Marion Gerson of Sheffield Hallam University in the UK and Professor Bill Meeker of Iowa State University, USA. Dr Gerson reviewed the course as the official representative of the RSS. Following an initial review, changes were made to give more emphasis to the uncertainty attached to engineering conclusions based on statistical analysis. In particular, revisions were made to the exercises to ensure that they did not give the impression that statistics is a deterministic science. After a second review and on Dr Gerson's recommendation the statistical content was approved by the RSS and the course was made available to UK universities through the Engineering Learning and Teaching Support Network at the University of Loughborough. Professor Meeker commented that 'more than any other course in engineering statistics that I have seen, this course would seem to have the potential to provide the knowledge necessary to apply modern methods of robust design, experimental design, and process monitoring and control to the important problems of product and process design.'

In 2002 Ford developed a Web-based version of the course, which has largely replaced the instructor-led training. The Web-based version is available to a global audience in Ford in both the English and German languages. It is used within the company to support the training of engineers in connection with DfSS.

DISCUSSION

We believe that the problem-based approach, with engineering tasks drawn from the product creation process, has been very successful. In addition to the internal Ford training for which the course was primarily designed, the University of Bradford has hosted short courses attended by staff from local companies with non-automotive interests, by university research staff and by part-time Masters students. Use of the materials on full-time undergraduate and postgraduate programmes has continued at the universities of Bradford, Southampton and Glasgow Caledonian. In addition, sections have been used at other UK universities including Coventry, South Bank and Sheffield Hallam. The feedback we have received from this very wide range of participants is overwhelmingly enthusiastic.

It is perhaps of interest that our own perceptions of the course changed considerably during its development. In response to Richard Parry-Jones' promotion of statistical engineering, our initial focus was on raising the level of statistical competence amongst engineers. The working title for the course was either Statistics for Engineers or Engineering Statistics. For the reasons discussed earlier, we believed that statistical learning would be enhanced by a problem-based approach. However, the substantial engineering content has taken on a life of its own, and we now use the title Statistical Engineering. The course has a dual function, teaching engineers the fundamentals of the product creation process ('doing the right things'), as well as many of the statistical methods which are needed within that process.

The nature of the materials has, however, led some observers to the misperception that a 'foundation' course in statistics is a pre-requisite for the course. The origin of this idea may be the unconventional order of the presentation of statistical ideas, or the inclusion of topics such as multiple regression which would not usually feature in an introductory course. An additional difficulty for people with a strongly orthodox view of statistical education may lie in the fact that statistical inference is not covered formally within the course. Instead, hypothesis tests and confidence intervals are treated informally as aids to inductive reasoning.

Looking to the future, we plan to enhance the case study by exploiting a finite element model of the pin/stay mechanism on the FFD which has been developed by Dr George Rosala of the University of Bradford. The model could be used to generate data for exercises, either as pre-written material or as interactive sessions within the course. Using a CAE model in designed experiments would help to link the course to the best practice in modern engineering design.

An electronics case study has been developed to match the statistical engineering teaching materials by Dr Elaine Smith of Glasgow Caledonian University. We would like to encourage other authors to develop alternatives to the FFD storyline in order to align the materials with the interests of other groups of engineers.

The course materials can easily be extended or deepened, keeping the structure intact. For example, the version used with full-time M.Eng. students at Southampton University goes into more detail on the design and analysis of response surface experiments. We would like to develop a follow-up course which is based on another circuit of the product creation cycle, covering topics such as life data modelling and optimisation in greater depth. More generally, the task-based approach can easily be adapted to cover related engineering methodologies. For example we note that Davis [14], developing the ideas of Box [15] in an engineering context, has recently drawn attention to the important interplay between deduction from physical knowledge and induction from data. The task-based approach we have adopted would provide a good framework for teaching these ideas to engineers.

Acknowledgements—We would like to acknowledge the fundamental role played by Tim Nicholls in the development of the course. We also want to thank Tim Davis for his codification and championing of statistical engineering, Keith Ransom for his contributions to the materials, and Rob Herrick, Clare Morris, Neville Davies and Rob Eley for helping to shape and disseminate the materials.

REFERENCES

1. R. Parry-Jones, Engineering for corporate success in the new millennium, *The 1999 Engineering Manufacturing Lecture*, The Royal Academy of Engineering, London (1999).
2. J. Dewey, *Logic: The Theory of Inquiry*, New York, Holt and Co (1938).
3. A. Combes, C. J. Connolly and E. Henshall, Engineering quality improvement programme, *World Class Design to Manufacture*, **2**, 1995, pp. 17–24.
4. D. M. Grove and T. P. Nicholls, Statistics for engineering: a guided tour, *Proc. Industrial Statistics in Action 2000 Int. Conf.*, **1**, University of Newcastle-upon-Tyne, pp. 54–62.
5. P. Honebein, T. Duffy and B. Fishman, Constructivism and the design of learning environments: context and authentic activities for learning, in *The Design of Constructivist Learning Environments: Implications for Instructional Design and the Use of Technology* (eds T. M. Duffy, J. Lowyck and D. Jonassen). Heidelberg, Springer-Verlag (1993).
6. H. L. Oh, A changing paradigm in quality, *IEEE Trans. Reliability*, **44**, 1995, pp. 265–270.
7. I. F. Campean and D. Brunson, Design verification using customer correlated life prediction modelling, in *Global Vehicle Reliability* (eds J. E. Strutt and P. E. Hall) Bury St Edmunds and London, Professional Engineering Publishing (2003) pp. 71–94.
8. R. D. Webb, Investigation into the application of robustness and reliability tools to the design process, MSc thesis, University of Bradford (2002).
9. W. A. Golomski, Reliability and quality in design, *IEEE Trans. Reliability*, **44**, 1995, pp. 216–219.
10. M. Hu, J. M. Pieprzak and J. Glowa, Essentials of design robustness in Design for Six Sigma (DfSS) methodology. *SAE Technical Paper 2004–01–0813* (2004).
11. J. R. Savery and T. M. Duffy, Problem-based learning: an instructional model and its constructivist framework. *Educational Technology*, **35**, 1995, pp. 31–38.
12. A. Gros, Knowledge construction and technology, *J. Educational Multimedia and Hypermedia*, **11**, 2002, pp. 323–343.
13. A. Collins, J. S. Brown and S. E. Newman, Cognitive apprenticeship: teaching the crafts of reading, writing and mathematics, in *Knowing, Learning and Instruction: Essays in Honor of Robert Glaser* (ed. L.B. Resnick) Hillsdale, NJ, Lawrence Erlbaum Associates (1989) pp. 453–494.
14. T. P. Davis, Science, engineering and statistics, *The 2004 Engineering Quality Improvement Lecture*, University of Bradford (2004).
15. G. E. P. Box, Science and statistics, *J. American Statistical Association*, **71**, 1976, pp. 791–799.

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