Robust Engineering Design Post-Taguchi [and Discussion]

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Robust engineering design post-Taguchi

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A fundamental idea has emerged from the study of the work of Genichi Taguchi in off-line quality control. A product should be designed so that it is robust against variations in the manufacturing process and the environment in which it is used. But the idea is not entirely new. It appears in various forms in the vogues and syntax of modern engineering design. Thus we have 'design to product', 'design for manufacture', 'conceptual design and innovation', 'systematic methodologies' and so forth.

It is the ability to describe robustness in statistical terms that ought to create a change in design thinking. But for this to happen professionals on both sides need to understand each other's language. The paper attempts to bridge the gap by drawing heavily on the language of engineering design and giving recent examples of product design where both modes of thinking have benefited from each other.

1. INTRODUCTION

It is a remarkable fact that just as engineering design is beginning to emerge as a scientific discipline from an *ad hoc* collection of creative methods it is being deeply affected by a new and alien ethic. This impact has come from a special group of techniques known as Taguchi methods. The beneficial effect has been a long-overdue importing of statistical analysis and experimental design in particular. Statisticians, passive by discipline, are knocking on engineers' doors with less timidity than before. The present authors, each, it is to be hoped representative of their own cultural traditions gratefully accept the Society's invitation to try and make some sense of the different ideas and give some pointers to the future.

2. ENGINEERING DESIGN METHODOLOGIES

Of the several attempts to consolidate the techniques of engineering design, the one that has influenced thinking, particularly in Europe, has been the systematic design of the West German school. The first professional Chair of Engineering Design was inaugurated there in 1965 at the Technical University of Munich and has led to a very active period of research. The bible of this school is the work of Pahl & Beitz (1984). Systematic design is a serious attempt to break up the design–manufacturer–use routine of product development into conceptually manageable components. The four components are

(i) functional interrelationships: sorting out the function of a product, what it is as a system in its own right;

(ii) working interrelationships: the geometry, materials and physical principles involved;

(iii) construction interrelationships: assembly and manufacture;

(iv) system interrelationships: the interaction between the product and the human environment.

Associated with these are prescriptions for different branches such as electrical, mechanical and software design. There is some attention to engineering precision and feedback in product development but the method is really designed to systematize the process and leaves little room for mistakes. There is a healthy use of databases following the incorporation of computer aided design (the 'CAD system'). The method is 'step by step' and somewhat rigid although it is argued that it complements rather than inhibits the more intuitive creative processes. For summaries of this and related work see Eder (1987).

Developments in the U.S.A. and U.K. have been influenced by attempts to understand the psychology of creativity. The phrase 'conceptual design' summarizes these ways of thinking, which are either advocated by research workers or are perceived as already being used by professional designers (French 1985). They stress the dynamic and adaptive nature of the creative process. The image presented is of the designer sitting at the hub of a wheel towards which a number of inputs are pointed such as design specifications and CAD and from which the outcomes would be prototypes, drawings and flow sheets. One part of the approach is the production of many alternative solutions or configurations through which the designer would search in much the same way that a chess player searches through moves. This is called the 'combinative approach'. The alternatives will include means of performing essential functions, solutions to smaller subproblems, special geometric configurations and so on. For each such solution the characteristics would be evaluated and poor solutions thus eliminated. The method is time consuming but has the advantage of generating many untried solutions. A major report summarizing the United States' perspective is Rabins (1986). The conceptual design approach has been well represented in the U.K. at the Royal College of Art.

Both systematic and conceptual design have been greatly influenced by CAD and mathematical procedures. CAD has eliminated much of the drafting labour that has slowed up the creative process in the past. Mathematical optimization methods, already well developed in operational research, have speeded up the search for good solutions. CAD suites, in areas such as automative and aeronautical design, structural engineering and the design of electrical circuits, incorporate optimization and other methods such as finite element methods and simulation.

There is unanimity on the need to make use of the computer for data storage generally and for component and rule bases. Many of the interesting questions are unanswered, for example, how best to store the geometry and function of small components in matrix form. One can imagine a vertical axis with the geometric measurements and other characteristics and a horizontal axis containing details of the function, performance, variability, contact with other parts and so on (see the section on knowledge engineering in the ICED volumes (Eder 1987)). Rule bases store established engineering practices and feasible manufacture. Material bases can be updated with test information on new and perhaps composite materials. This 'knowledge engineering' will also provide an essential teaching resource and universities and colleges can play a leading role if given support.

Certain specialized topics have had periods of fashion within this general framework. 'Design for manufacture' and 'design for assembly' are self-explanatory and relate particularly to mass production. They highlight the occupational gap between design and manufacturing.

Economic forces, particularly competition from the Far East, have encouraged a broader analysis of design and manufacturing in the West. We shall address the largest effect, that on quality control, shortly, but there are others. Marketing and market research have influences back to design. Does a company really 'know what it is selling to whom and in what circumstances'? (special issue of *Design*, 1983). Also, British manufacturing industry has too heavy an emphasis on mass production. This makes the design process less flexible. In Italy, where designers have historically had higher status and hence more control over manufacturing, there are shorter production runs and shorter design times. There is a proliferation of smaller production units, for example in the Milan area, which can quickly 'tool-up' for a new product. This encourages the taking of risks. It is also helped, of course, by a greater awareness of good design by the Italian public. Here is a cutting quotation by Marrello Minale of Minale, Tattersfield and Partners.

> The Italian furniture industry can and does launch a new design within six or seven weeks of seeing it. The British industry hesitates over anything new, looking for a similar sort of design already on the market for encouragement. It is no wonder that the Italian industry has a reputation for flair and imagination while the British industry languishes beneath a reputation for dull and dated designs. (Rothwell *et al.* 1986.)

One outcome of the decrease in a product's 'lead-time' is the increased importance of *redesign*. Companies need to be able to take a product in which, say, a competitor is obtaining the advantage, and redesign it quickly. This may well mean updating or changing the previous methodology so that the product will perform its function better, have fewer components made of better materials and be easier to make.

Enough is now understood about the process of designing, making and selling a product to be able to draw suitable flow charts. One of the newer lessons is to bring as much information from manufacturing and marketing back to the design stage, the 'front end'. (The discussion process will to some extent be iterative between design and production, but a design once finalized should only be changed within a properly constituted redesign operation.) Thus flow charts have arrows going backwards to the designer which represent specifications and database information. We term this integrated approach *design-to-use*. Many companies have developed such charts and associated management structures for product development. Whether deliberately based on current academic thinking or not, they represent a blending of the ideas of systematic design with the creative knowledge-based approaches of conceptual design and mixed with a healthy dose of market research.

3. THE TAGUCHI PHILOSOPHY

The United States and United Kingdom are in the middle of a long-overdue revolution in quality improvement which is taking place at two levels. The first, and more general, arises from a response to the success of the management and quality control methods in Japan associated with the work of W. E. Deming. The second, which most concerns us here, is the result of the application of certain statistical methods to engineering design by Genichi Taguchi. Whether either can force changes to successful ways of working in continental Europe (we are thinking of West Germany and Italy in particular) will be interesting to observe. We feel that for this to happen some understanding of the relationship between statistical and engineering methods is needed.

The literature on Taguchi methods is growing fast and there are several excellent summaries (Box 1988; Leon *et al.* 1986; Nair & Pregibon 1986). There are active centres in the U.S.A. and Canada (for example at the Universities of Wisconsin and Waterloo).

The principal idea is that statistical testing of a product should be carried out at the design stage, the off-line stage, in order to make the product robust against variations in the manufacturing and use environments. Hence the widely used term 'off-line quality control' (or quality improvement). This is different from on-line methods, such as inspection sampling, coming under the broad heading of statistical quality control and statistical process control (SPC).

Secondly, quality is measured by statistical variability such as standard deviation or mean squared error rather than percentage defects or other more traditional tolerance-based criteria. The main criterion is either keeping the performance on a target value, c, while minimizing variability, or optimizing output while minimizing variability. In fact these criteria are not new, being already the basis for on-line control engineering (e.g. quadratic control (Caines 1988)). But their use in the 'static' control of engineering design seems to be very new.

Thirdly, Taguchi draws a distinction between design parameters, or variables, over which the designer has control (input controls in the system sense) and noise variables. The idea of varying the design parameters as inputs to achieve target is not new. The important contribution is the systematic inclusion into the experimental design of noise variables, that is variables over which the designer has no control but which can be controlled in an experiment. A distinction is also made between internal noise, such as component wear and material variability, and the external noise just mentioned. Taguchi also divides the design variables where possible into those which affect mean response and those which affect the variability. This terminology has given statisticians and engineers a common language with which to discuss particular examples.

Tolerance design is an additional part of the philosophy. Briefly, this means analysing the effects of internal noise and tolerances on performance. An aim here may be to replace a component which does not affect output variability with a cheaper component in redesign. It should be noted that a considerable amount of work in this area predates the use of the Taguchi methods, particularly in the field of electrical engineering. For example, work in circuit fabrication by A. T. & T. Bell Laboratories and collaborators has systematically used simulation methods to analyse variability in circuit performance arising from the fabrication process and using the analysis in circuit design. The collection of papers from their recent conference are representative of this work (A. T. & T. Bell Laboratories 1986). The simulation of circuits in very large-scale integration (VLSI) is a proving ground for many established mathematical techniques: stochastic optimization, stochastic approximation, computational experiments (simulation design) and variance reduction.

A brief summary of the general method of VLSI is as follows. An integrated circuit is fabricated in a complex and partly continuous process. A circuit simulator such as SPICE can design to specification up to a certain point. But the behaviour of the circuit will depend critically on the physical characteristics of its subcomponents or 'devices' such as transistors. These in turn depend on the fabrication process to the extent that users have to incorporate information from fabrication into their use of the circuit simulators. Here the future lies with fabrication simulators which accurately summarize this information. The inputs to such simulators are from physical models of the individual parts of the process.

> The process simulator, FAB 1, contains a library of models of manufacturing operations, as well as libraries of functions that simulate impurity profiles and extract in-line parameters from the simulated profiles.... (Nassif *et al.* 1984.)

In terms of the Taguchi terminology a rough division is that the design variables are set in the inputs to the circuit simulators and the noise variables represent the variations in the devices determined by the fabrication simulator.

4. A SYNTHESIS

A main contribution of Deming, and one recognized in Japan thirty years ago, is the necessity of moving quality control backwards from inspection to proper process control. Control the process and inspection becomes unnecessary. We can see the contribution of Taguchi as a shift still further back to design. The principles, however, are the same and *control* is the best word to summarize them. It is a stronger word than system theory and already represents, in time-domain dynamic and adaptive control, a fully fledged discipline. The systems approach of systematic design is clearly correct but what is lacking is a notion of *static* control in which time as the index of action is replaced by a spatial and physical one. The input controls (design variables) become based on geometry, structure, materials, tolerances and so on; but the objectives will be similar.

If x denotes a set of design variable levels and $Y(x)$ denotes the response, then we first seek to build a component. Thus, set x to minimize $\phi(Y(x), c)$ where ϕ is some function which takes into account the variation in Y and the distance from the target c. For example, we may set $\phi = E(\psi(|Y-c|))$, where E denotes statistical expectation and ψ is some increasing function. Statisticians can recognize ϕ as a proper risk function, ψ being the loss function. The source of variation here is from the variation over the noise variables.

If $\psi(r) = r^2$ then

$$\begin{aligned}\phi(Y, c) &= E((Y(x)-c)^2)\\ &= \operatorname{var}(Y(x)) + (E(Y(x))-c)^2,\end{aligned}$$

ϕ is mean squared error, var is variance and the last term is squared bias. In this case an unbiased solution would be to choose $x = x^*$ to achieve

$$\min \operatorname{var}(Y(x)) \quad \text{subject to} \quad E(Y(x)) = c.$$

Both $E(Y(x))$ and $\operatorname{var}(Y(x))$ have to be estimated from experimental data. If the estimates are $\hat{Y}(x)$ and $\hat{\sigma}^2(x)$, the optimization problem becomes stochastic and if x^* is the solution, this too depends on the data. In control theory $Y(x)$ is a future observation Y_{n+1} and we would choose input controls to force $\hat{Y}_{n+1} = c$.

A more detailed formulation separates the x variables into design and noise variables, x_{d} and x_{n}, as explained, for example, in circuit simulation. Then Y becomes a function of both, $Y(x_{\mathrm{d}}, x_{\mathrm{n}})$. The risk can usually be expressed as an integral or average over x_{n} and, if tolerancing is important, over small variations in x_{d} also. Thus we want to minimize

$$\int\!\!\int \psi(Y(x_{\mathrm{d}}, x_{\mathrm{n}}))\, p_1(x_{\mathrm{d}})\, p_2(x_{\mathrm{n}})\, \mathrm{d}x_{\mathrm{d}}\, \mathrm{d}x_{\mathrm{n}}$$

for some density functions $p_1(x)$ and $p_2(x)$. Taguchi's method of averaging over the noise variables can be seen as a cheap method of integration. An alternative is to fit Y directly to both x_{d} and x_{n}, and perform the integration on $\psi(\hat{Y}(x_{\mathrm{d}}, x_{\mathrm{n}}))$. For example, we may want an estimate of the probability of $\{Y \geqslant c\}$, sometimes referred to as the 'yield', in which case ψ is just the indicator function. It seems very natural to use $\{\hat{Y} \geqslant c\}$ instead.

The functions applied in this area of quality control are often cases of 'mean-risk' or 'mean-variance' risks, i.e. risks that seek to optimize a function of both the mean output and minimize some measure of variability. Although to some extent neglected in the statistical literature, this is not so in mathematical economics where they have received considerable attention in areas such as portfolio analysis; see Wierich (1987) for a recent reference.

In engineering design x lies in a wider class of configurations. A second main theme is therefore to define some space of allowable configurations for the design variables. We shall call this the design space. The literature refers to 'catalogues', 'exploration of design alternatives' and so forth. The design space for experimental design is enlarged to include any noise variables. Experimental design methods select a small subset of the experimental design space at which to make observations. This means making a small set of products (or varying the settings of products) for testing. In the presence of a suitable mathematical model it is not necessary to look at all configurations, but only to look at some and extrapolate or interpolate for the others. The saving in time in doing this is one of the biggest contributions that statistics can make to engineering.

The distinction between controlled experimentation and passive observation is an old one. John Stuart Mill talks about 'artificial' and 'spontaneous' experiments (Nagel 1950). What exactly do we mean by variability in $Y(x)$? It is clear that differences between products with the same x, can increase throughout the birth and life of a product. Sampling and rejection is a last-minute attempt to decrease this variability. A robust design should limit this variability from the outset. But a highly controlled experiment which does not measure the variability cannot help to make a design robust. We feel some new word is needed to describe this spectrum of possible experiments, at one end of which is the pure controlled experiment and at the other end of which is testing, in use, of a fabricated product (for example, vehicle test driving). As we proceed along the spectrum we acquire greater knowledge of the true sources of variability.

This idea is described schematically in figure 1, which has proved useful as a discussion tool. For example, we cannot emphasize too strongly the importance of good shop-floor data collection not purely for process control but for design. We choose the word *immersion* to describe this process.

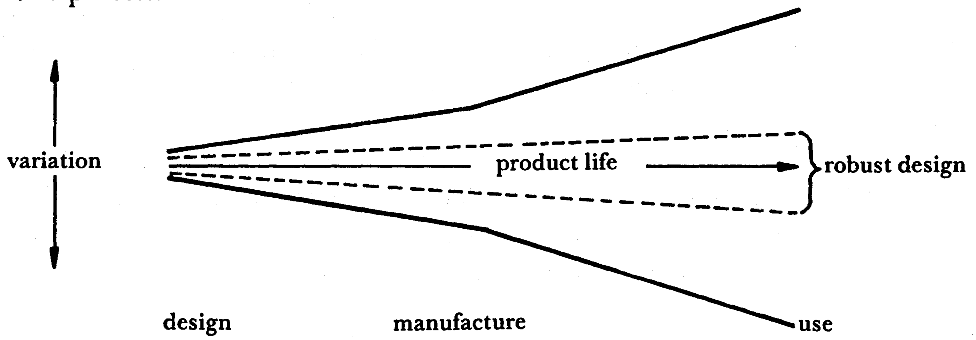

FIGURE 1. Immersion.

Our own conclusions for engineering-design methodologies favour the conceptual approach, but with additional components. The designer, and we should have been using the phrase 'design team', needs to have enough and as many different kinds of information at his disposal so that he may immerse himself in the life history of the product and be able to identify the sources of variability referred to above. He needs to surround himself with the necessary equipment for doing this. Nowadays this will invariably be computer based. Here is a fairly complete list of modules which take into account our discussion.

1. A graphics facility.
2. CAD software.
3. Rule and component databases.
4. A manufacturing tolerance database or a manufacturing simulator.
5. Model building and simulation packages.
6. An optimization package.
7. A computer-aided experimental design package.
8. A statistical analysis package.
9. A tolerance design package.
10. Market research data.

The more general methodology will then be defined as the utilization of the modules, namely the order of use, the importance of any module and so on. Of course, specific methodologies will be associated with each module. We are concerned to link together the modules rather than shout the virtues of one above another. In figure 2 we sketch a flow diagram of the use of the modules built around the idea of design spaces.

The diagram is roughly divided into four phases. The first is the construction of the design space of allowable configurations. This may be based on some initial design, but will certainly be greatly influenced by access to component databases. Its construction is also based on

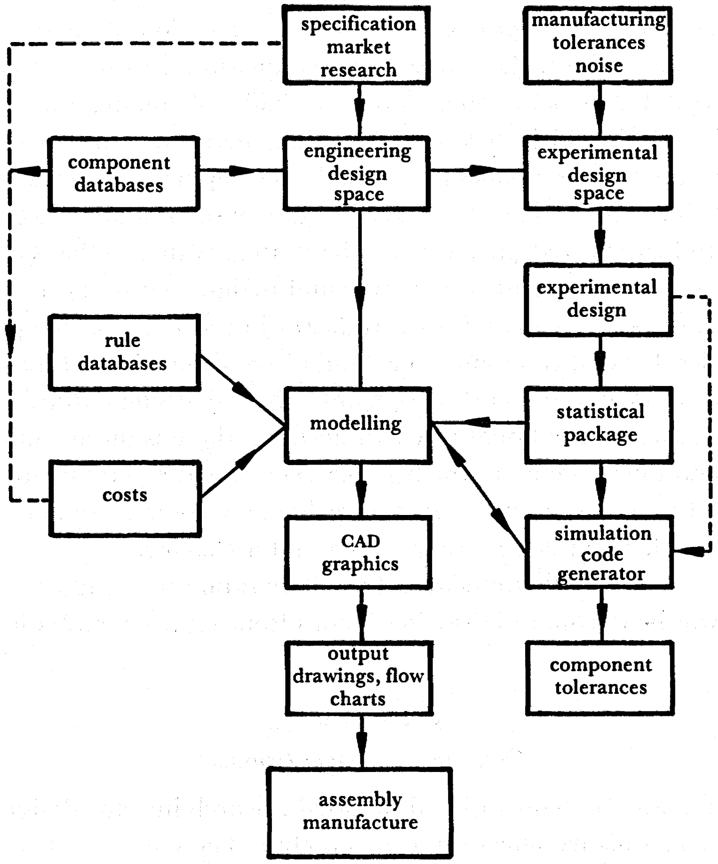

FIGURE 2. Methodology.

Taguchi's 'system design' activity or the first phase of the systematic design approach, i.e. sorting out the function of the product. We may proceed directly to modelling and optimizing (deterministically). Indeed, some initial modelling will help to determine the design space.

Another route is to carry out experimental testing, where possible enlarging the design space by including noise variables. This is the second phase.

After statistical analysis we may have an empirical model or have estimated more precisely parameters of an initial model, or changed it. One should also have a clearer idea of sources of variability and seek to eliminate them. The model will usually be based on physical and engineering principles some of which may be stored in databases. Costs are also very relevant: component costs, assembly costs, manufacturing costs. Once an initial model is implemented simulation experiments, themselves properly designed, can be performed to ascertain the effect of the components' tolerances, sequentially optimize the design and so on. This is the third phase.

Finally, we proceed to detailed drawings and the route to assembly and manufacture. Taguchi's method of (i) system design, (ii) parameter design and (iii) tolerance design is a brilliant summary of this route, but needs to be expanded to include a view of the management of the various modules which we have listed. In particular a reconciliation with existing computer-based technology and engineering design philosophies is essential.

The management of the modules is best carried out by using a shell expert system, the real expert being the designer, at least for the next few years! The menu-driven facilities are already being used to home in on suitable sublists of components and store assembly and manufacturing costs. Modern experimental design packages allow specification of factor levels. It should be noted that there are two kinds, those based on combinatorial principles and those based on optimum experimental design methods. The possibility of linking these with existing CAD packages is exciting. It is widely acknowledged that many CAD packages have inadequate tolerancing and simulation components although development is rapid in this area. Good statistical principles are urgently needed here. The design of simulation experiments is another very active field and specialized packages are becoming available (Sacks *et al.* 1989). These allow the specification of very general experimental design spaces and models.

The post-Taguchi era is already with us. Industry in the U.K. is well placed to assimilate the new philosophies. Several companies have imported Taguchi's methods with zeal and are melding them with work in product development. There is strong enthusiasm for both design and quality improvement at national level. In addition there is input from the 'style' end of design in fashion and the visual arts, which seems to have had a permanent renaissance dating back to the 1960s. In schools, craft design and technology courses are flourishing and there is upward pressure on places in engineering design and art colleges.

Our thinking has been greatly influenced by collaboration with industrial partners and the rest of the paper will be devoted to drawing lessons from some examples in order to flesh out the arguments.

5. EXAMPLES

Example 1: pressure transducer

Lucas Engineering and Systems Ltd had initiated research into the design of a new pressure sensor using the piezo-resistive effect on a silicon chip. The chip acts as a diaphragm whose stress changes with pressure and hence affects the resistance of attached piezo-resistors. Over 200 chips at a time are cut from a wafer. There are competing foreign makes with different designs. In all designs, however, the diaphragm is supported by a pillar with a vacuum beneath the diaphragm. The pillar in turn is supported by and housed in a casing (figure 3). A standard electric circuit picks up the change in resistance and converts it into a reading.

The reading should be linearly related to the pressure (figure 4), the line having a slope and intercept (offset). The offset must be estimated and corrected electrically to produce a reading. However, the offset is sensitive to temperature. Thus a key aim of the design is to identify the design features which affect this offset variability and to remove it.

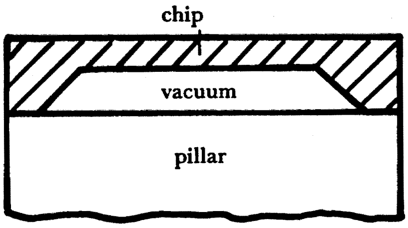

Figure 3. Pressure sensor.

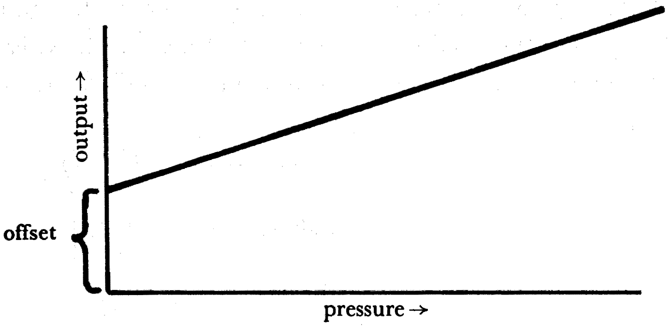

Figure 4. Offset.

The noise variables are the temperature and the pressure because they are *not* part of the engineering design. Replication of these for different builds is facilitated by a controlled test rig which can produce (overnight!) a large number of pressure–temperature combinations. The experimental design used two replicates of eighteen different builds which had different combinations of geometry and materials. A hundred (10 × 10) pressure–temperature combinations were taken on each build. Only the points which help our discussion will be given here.

1. The principal aim is the minimization of variability. The attainment of targets can be achieved electronically once this 'nuisance' has been removed.

2. Some of the variability is due to the chip itself. Considerable effort is needed to check the spatial variability in the surface of the wafer from which the chips are cut. Tolerances of bought-in components must be taken into account. One man's component tolerances are another man's manufacturing tolerances.

3. Temperature characteristics of certain materials, composites and adhesives are not well calibrated. Separate testing and construction of databases are required.

4. Replication, an essential part of the estimation of variability, is greatly helped if it can be performed automatically. Notice the difference between replication of components (expensive) and repeated measurement on the same component (cheap).

5. Different parts of the sensor had different amounts of scientific modelling associated with them. The piezo-resistive effect and the chip design benefited from a separate research programme. The temperature characteristics of the pillar and casing relied on more empirical, subjective arguments.

6. Certain builds were easier to manufacture than others. Thus the design process may affect the manufacturing; for example, recommendations on the application of adhesives in production.

The two principal aids to thought which this talk is promoting are borne out by this example. Discussions were very much centred on the engineering or experimental *design spaces*, the function already being well specified. For example, the discussion of different geometries was a stimulating exercise. Secondly, as the project proceeded and more sources of variation became apparent, the feeling of immersion prevailed, though expressed verbally in different ways. This all points to the importance of 'brainstorming' sessions early on.

Example 2: *lash adjuster*

GKN Technology Ltd have developed an automatic mechanical lash adjuster (AMLA) to replace the usual hydraulic tappet system which is sensitive to oil-borne sludge and air in the oil. The AMLA maintains a constant gap under all conditions of engine temperature and wear, eliminating the need for manual adjustment of the valve train. It consists of an inner threaded component, an outer body, and a nipple and spring (figure 5).

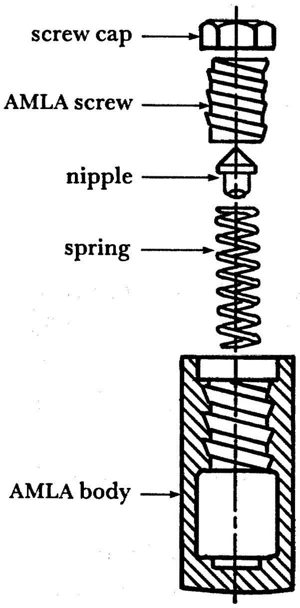

FIGURE 5. AMLA geometry.

The adjuster is relatively easy to manufacture, but because of the geometry of the body it requires a more difficult tapping operation. The critical quantity is the axial clearance between the adjuster and the body; too small means too tight a fit and too large could result in noisy operation of the AMLA. There is tool wear during the process of machining and the clearance is also affected by heat treatment.

The development work having been completed, various trials were conducted to optimize the manufacturing process and again lessons were learnt.

1. The sophisticated geometry of the design forced improvements in manufacturing.
2. Setting the correct tolerances is vital. Absolute tolerances fixed at the design stage can be affected by the manufacturing process.
3. Separate experiments were necessary to build models of the manufacturing process. Initially these were required to speed up the evaluation of tapping trials. It was found for example that variability was constant over drill-bit life so that later trials required less replication and more effort could be put into minimizing variability.
4. Tapping data should be available to the designer. Although this may be specific to the product some database of relevant information would be useful.
5. Component materials are also an important factor in manufacturing tolerances.

Example 3: *audio filter*

This example is from Dr N. Logothetis of GEC Research. The objective is the optimization of two phases of a high-pass audio filter circuit used in mobile radio transceivers. The filter consists of four resistors and four capacitors. An adverse effect on the amplitude of the filter was experienced, and was due to component tolerances. The objective was to optimize the filter's design keeping the same component tolerances. The response was proportional to the logarithm of the ratio of input to output amplitudes, in decibels (figure 6). There was a computer model of the filter on which experiments could be performed. The design factors served as both design variables in the usual sense and noise variables. This is done by varying the levels of the variables around nominal values to simulate variation arising from component tolerances. There were 18 combinations of tolerance levels (outer array) at each of 18 combinations of nominal values (inner array), both chosen according to an orthogonal fraction of 2×3^7 factorial design. The means and standard deviations are presented in table 1.

An optimum setting of the components was sought leading to a mean value less than 0.70 with small standard deviation. A combination was found with estimated mean at 0.5743 and standard deviation 0.0379, a considerable improvement. The result is a filter circuit which is less sensitive to the effects of tolerance without the need to improve component tolerances.

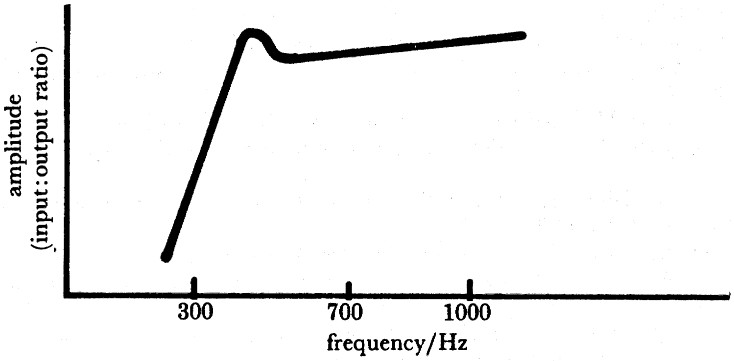

FIGURE 6. High-pass audio filter.

TABLE 1. HIGH-PASS FILTER

trial (inner array)	mean	standard deviation
1	0.21722	0.033754
2	0.77758	0.081038
3	1.06540	0.031802
4	0.89102	0.048586
5	0.53990	0.050371
6	0.85181	0.087033
7	0.93021	0.033125
8	0.61971	0.044268
9	0.62674	0.056152
10	0.61042	0.072067
11	1.18810	0.036843
12	0.56260	0.086894
13	0.66359	0.064258
14	0.81278	0.099847
15	0.98423	0.036795
16	0.76133	0.057136
17	0.66780	0.063613
18	0.96238	0.035476

This supports the use of what we call phase three above, i.e. the use of well-designed computer experiments to improve a product's performance. There are two levels at which model building takes place, the computer model (deterministic) and the statistical model (partly stochastic). Dr Logothetis describes the method as 'parameter design through tolerance analysis' in the sense that the need to tighten components tolerances was avoided by selecting optimum settings. Thus the method is also a hybrid between our phase two and phase three.

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Discussion

S. M. Rizvi (*Polytechnic of Central London, U.K.*). Economists tell us that increases in productivity are associated with increases in production (Verdoorn's law). We also know from experience that when organizational structures become larger the quality of the output declines. It is true for the agricultural sector, the service sector and also for the industrial sector. Thus productivity and quality are inversely correlated. How can we advance both of them simultaneously? Can smaller production units solve this problem?

H. P. Wynn. Smaller design and production units may allow a quicker and more flexible response to market forces, particularly at the 'quality goods' end of the market, e.g. Italian furniture design. Further, modern improvements in quality require involvement by the whole product development team, and communication may be easier in smaller units. There are also important and well-documented differences in cultural attitudes to design and creativity in the two countries.