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A Model for the Measurement of Creativity. Part I: Relating Expertise, Quality and Creative Effort*

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As a first step towards a methodology for the measurement of creativity, quantified definitions of product design quality, designer expertise and creative effort are introduced in such a way that their interrelationship can be portrayed as a set of hyperbolic curves, the c_EQe_X diagram. Product quality is mathematically related to the product characteristics. Designer expertise is defined to include all the invested tertiary education and relevant experience contained in the design team, as well as investment in design software and laboratory facilities. Designer creativity is defined to be proportional to (a function of) product quality obtained and inversely proportional to the product of (a function of) initial expertise and creative effort expended. Guidelines for the construction of the c_EQe_X diagram are given. The c_EQe_X technique holds potential for the measurement of creativity and is useful as a guide for curriculum development.

NOTATION

Capital letters

A	constant
$A(Q)$	area associated with Q on c_EQe_X diagram
B	function of product characteristics depicting physical boundaries
C_E	creative effort
C_{EF}	creative effort required to access facilities
C_i	*i*-th characteristic of product
C_{bi}	physical boundary of C_i
C_{Si}	specified requirement for C_i
$C_E(Q)$	E_X-independent part of C_E
E_d	invested education
E_{dr}	relevant invested education
E_X	expertise
K_Q	function of Q
N	number of product characteristics
N_{ed}	number of years of invested education
N_{exp}	number of years of relevant experience
P	product performance function depending on product characteristics
Q	product quality

Lower-case letters

c_E	non-dimensional C_E wrt E_{XR}
$c_E(Q)$	e_X independent part of c_E
c'_E	$c_E(Q)/e_X$
c_i	non-dimensional C_i wrt C_{Si}
c_r	creativity
e_X	non-dimensional E_X wrt E_{XR}
$\hat{e}$	unit vector
$g(E_X)$	function of E_X
k_Q	function of Q
m	exponent in $C_E(Q)$
n	exponent in $C_E(Q)$
n_D	number of engineering disciplines
n_f	number of relevant facilities
n_m	number of team members
w_i	weighting value

Greek letters

α	experience amplification factor
β	overlap factor
Γ	constants in $C_E(Q)$
γ	constants in $c_E(Q)$
δ	constant
η	thermal efficiency

Subscript

R	reference designer

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INTRODUCTION

TO BE creative is deemed to be an important quality in probably every field of human endeavour. The topic has been researched by academics from many different fields such as psychology, education, philosophy, architecture and engineering and much effort has been devoted, on the one hand, to the identification of the special human characteristics which lead to creativity, and to the ways that creative people perform their creative deeds. On the other hand, it appears that there does not exist an accepted method for the measurement of creativity in individuals or in a group of persons working collectively on a creative project.

Based mainly on insights gained as a practising systems engineer for the design of complex engineering systems, the author proposes a guiding model for the measurement of creativity below.

The model relates product *quality*, designer *expertise* and designer *creative effort* in such a way that creativity can be calculated as a function of time as the creative process proceeds. The model shows what demands are placed on the designer to ensure quality designs and as such hints at engineering curriculum and syllabus design.

The model approaches creativity *from the outside looking in*, i.e. it evaluates creativity by looking at the quality of the product (the consumer's view) which is being formed, duly considering:

(a) the effort which has been spent on the process (the investor's view) and
(b) the level of appropriate education of the creator (the educational establishment's view).

It is neither concerned with any other characteristics of the creator nor with the details of the process which is followed, quantities which would be important if creativity were analysed *from the inside looking outward.*

A schematic presentation of the present model is shown in Fig. 1. As shown, the designer 'absorbed' prior education and experience from the outside world, which also supports him financially, and for which he develops a product of a certain quality. Any other creative characteristic, e.g. attitude, judgement and motivation [1] is included in the shaded segment as it influences the present definition of creativity only indirectly. For the same reason details of the creative process which is followed [2–7] are contained in a shaded segment. It is assumed that favourable creative characteristics and processes would imply a reduced required creative effort to develop a product of a certain quality. The reduction in creative effort would imply a measurement of increased creativity.

The paper begins with some relevant comments on the creative process as used in systems design. In preparation for a more rigorous subsequent treatment, a superficial introduction to the creative effort-quality-expertise ($C_E QE_X$) diagram is given in the following section. This is followed by discussions on topics such as product design characteristics, quality, designer expertise and creativity; each being carefully defined such that they can be mathematically interrelated. In Part II it is shown how the $c_E Qe_X$ diagram, a dimensionless form of the $C_E QE_X$ diagram, can be used as a nomogram for the graphic portrayal of creative processes and how the present model may be used for the measurement of creativity by means of a case study.

THE CREATIVE PROCESS

Creativity is a popular topic for discussion in the literature. The Oxford dictionary defines being creative as: *to form out of nothing*, a definition which covers most others put forward in other sources. As the present study examines creativity from the outside looking in it is not essential to consider the exact form of the creative process that the designer follows. It will suffice to consider a single (but crucial) facet of the creative process,

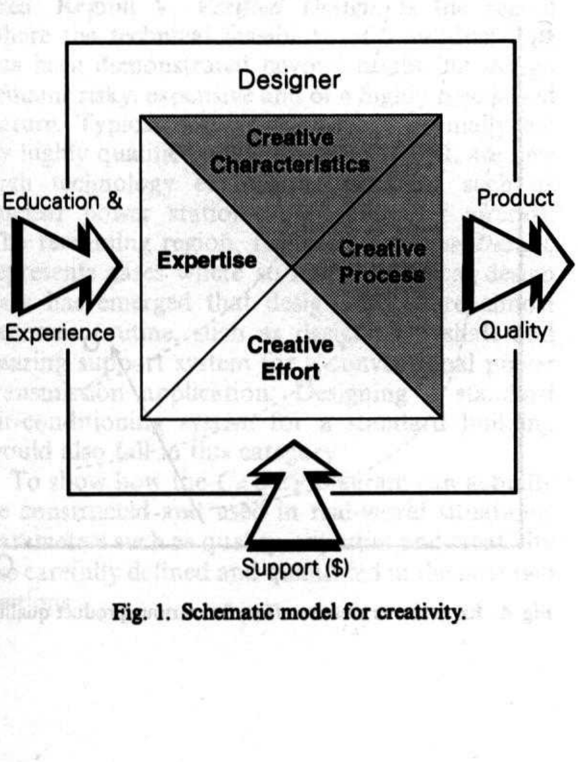

Fig. 1. Schematic model for creativity.

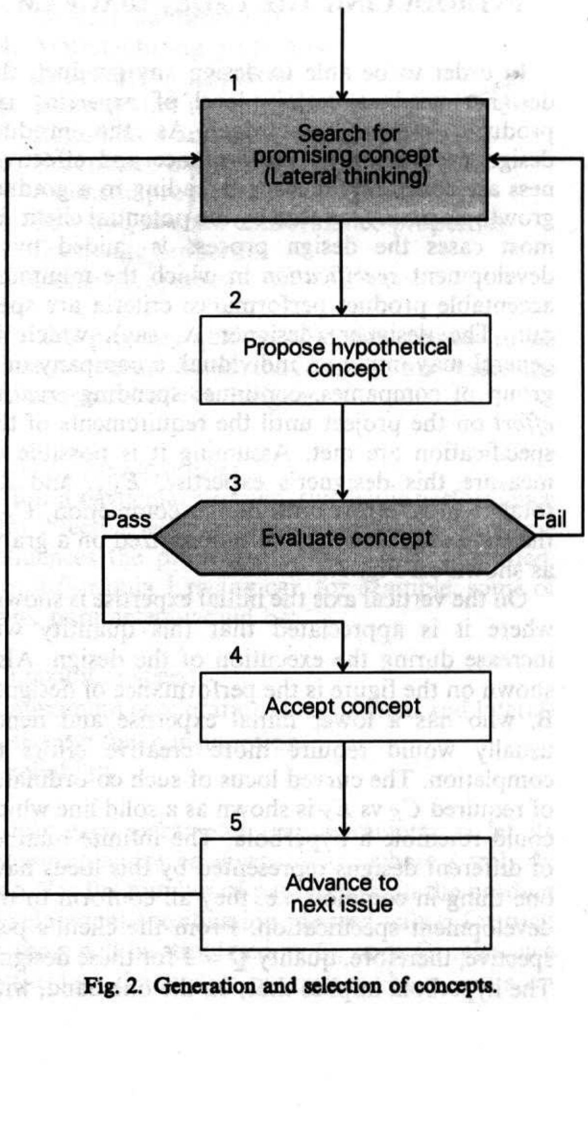

Fig. 2. Generation and selection of concepts.

that of hypothesis generation and testing as depicted by Fig. 2.

This model closely resembles the *basic design cycle* proposed by Roozenburg and Eekels [8] and the TOTE cycle (test-operation-test-exit) as a formal description of trial-and-error procedures in human problem solving, of Miller *et al.* [9]. Step 1, the search for promising concepts, relies heavily upon human creativity. What needs to be emphasised, though, is that the search for and evaluation and acceptance of viable concepts depends largely on the product-related knowledge or expertise of the designer. No matter how creative a group of poets might be, working together on the design of a high performance gearbox, it is unlikely that a useful solution will emerge. Vice versa, assigning an engineering student to compose a violin concerto would rarely produce a presentable result. In both cases the hampering factor is a lack of expertise, rather than creativity. Especially, Steps 1 and 3 are most efficiently executed when the designer combines original thinking with his comprehensive product-related knowledge. Put differently, the more expertise there is available, the less creative effort should be required.

INTRODUCING THE $C_E Q E_X$ DIAGRAM

In order to be able to design any product, the designer needs a certain level of *expertise,* i.e. product related knowledge. As the product design progresses, its performance and effectiveness are constantly measured leading to a gradual growth in *quality,* as seen by the potential client. In most cases the design process is guided by a development *specification* in which the minimum acceptable product performance criteria are spelt out. The designer (designer A, say), which in general may imply an individual, a company or a group of companies, continues spending *creative effort* on the project until the requirements of the specification are met. Assuming it is possible to measure this designer's expertise, E_{XA}, and his total creative effort until design completion, C_{EA}, the state of affairs may be summarized on a graph as shown on Fig. 3.

On the vertical axis the initial expertise is shown, where it is appreciated that this quantity will increase during the execution of the design. Also shown on the figure is the performance of designer B, who has a lower initial expertise and hence usually would require more creative effort to completion. The curved locus of such co-ordinates of required C_E vs E_X is shown as a solid line which could resemble a hyperbola. The infinite number of different designs represented by this locus have one thing in common, i.e. they all conform to the development specification. From the client's perspective, therefore, quality $Q = 1$ for these designs. The hyperbola implies that, on the one hand, with

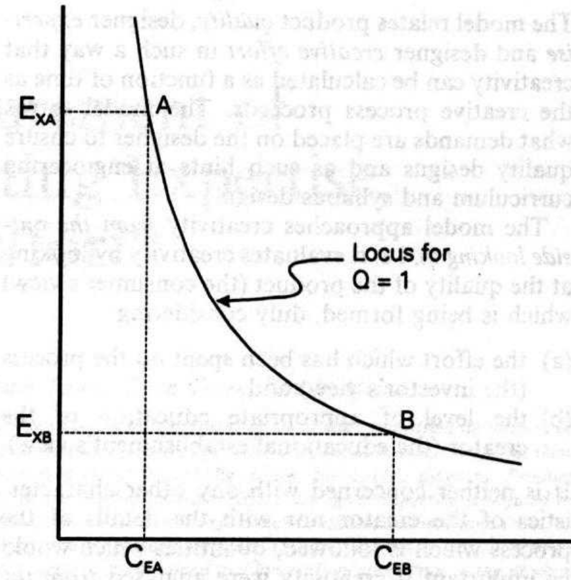

Fig. 3. Expertise vs creative effort for two designers.

little E_X a lot of C_E is required for an acceptable design and, on the other, a lot of E_X requires little C_E.

Assuming that premature termination of the design process results in an unfinished product with measurable quality Q, where $Q < 1$, graphs of required C_E vs initial E_X for various Q-values are shown in Fig. 4, henceforth referred to as the $C_E Q E_X$ diagram.

During and after the first appearance of a new class of engineering product (e.g. first aircraft, automobile or personal computer), expertise related to such a product evolves and becomes entrenched in growing amounts. The Wright brothers did not possess a comprehensive understanding of wing aerodynamics but by WWII volumes of design data on the aerodynamics of wing sections had appeared.

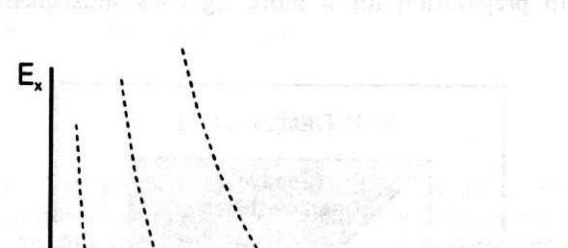

Fig. 4. Expertise vs creative effort for various product quality.

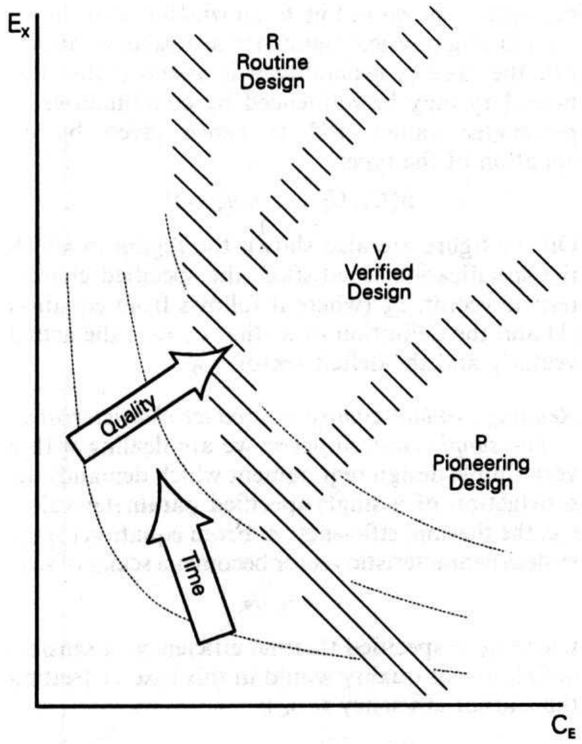

Fig. 5. Chronological development of product design.

Seen from a historical perspective then, design of a product range of fixed quality would chronologically proceed as shown by the arrow in Fig. 5. Region P, *Pioneering Design,* represents breakthrough, first-time designs where the designer initially hadn't possessed much expertise but had to invest a large quantity of creative effort for success. This is the world of historically original inventors such as James Watt and Thomas Edison. Due to the high associated development risks, designers are seldom contracted to work in this area. Region V, *Verified Design,* is the region where the technical feasibility of a product-type has been demonstrated beyond doubt but design remains risky, expensive and of a highly specialized nature. Typical designs, which are normally led by highly qualified engineering personnel, are new high technology engineering products such as nuclear power stations and commuter aircraft. The remaining region, region R, *Routine Design,* represents cases where so much empirical design data has emerged that design procedure almost becomes routine, such as designing a shaft and bearing support system for a conventional power transmission application. Designing a standard air-conditioning system for a standard building would also fall in this category.

To show how the $C_E QE_X$ diagram can actually be constructed and used in real-world situations, parameters such as quality, expertise and creativity are carefully defined and quantified in the next two sections.

QUANTIFYING QUALITY OF DESIGN

The quality of a product is of vital importance to the client or consumer. Hence designers must be highly conscious of the quality of their designs and must have means to define and measure it. Definition of quality is by no means trivial, as Pirsig [10] points out in his delightful book but, fortunately, seeing engineering products mainly as those having to fulfil *functions* and with measurable *performance,* it can be attempted.

The engineering literature contains lots of definitions for and discussions of quality. According to ISO 9000:

> Quality is the totality of the characteristics or performance that can be used to determine whether or not a product or service fulfils its intended application.

For the present it is important to distinguish between quality of design and quality of conformance [11]. In the following, quality will be restricted to quality of design. For a physical product a useful categorization of quality factors can be obtained by forming two groups of properties: 11 classes of externally visible properties plus the (invisible) internal ones [12]:

1. Functions, effects
2. Functionally determined properties
3. Operational properties
4. Manufacturing properties
5. Distribution properties
6. Delivery and planning properties
7. Liquidation and environment properties
8. Ergonomic properties
9. Aesthetic properties
10. Law and societal conformance properties
11. Economic properties
12. Design properties

For the present, quality of design relates to all those properties listed above which are under the direct control of the designer.

Product characteristics

For a particular product, the major performance and effectiveness parameters, of which each one influences the product quality, can be identified. For a Formula 1 racing car, for example, some of these parameters would be:

- maximum speed
- maximum acceleration (longitudinal and lateral)
- specific fuel consumption
- reliability.

For each parameter (say parameter i) let its measurable size be given by C_i, where $i = 1, N$, and N is the number of parameters. In the product development specification, desired values for each of these will be stipulated as C_{Si}, say. Of relevance is the fact that many parameters have limits on their most-extreme size, the latter quantity being determined by our current understanding of science, engineering and economics. Denoting these limits by C_{bi}, some examples are:

- Carnot efficiency
- speed of light
- zero absolute temperature
- zero production cost.

Now, after measuring each characteristic parameter for a product (which might still be under development) and having defined the set of parameters such that not one is redundant, the *system characteristic vector* can be defined as an N-dimensional Euclidian vector:

$$\underline{c} = \sum_{i=1}^{N} \frac{C_i}{C_{Si}} \sqrt{w_i} \hat{e}_i \qquad (1)$$

where $\hat{e}_i$ is a unit vector along axis i and w_i is a weighting value such that:

$$\sum_{i=1}^{N} w_i = 1$$

The Euclidian assumption requires all the vector components to be independent which is not true for the system characteristic vector when viewing it from the *inside* of the design process. For the client, who generally is not concerned with engineering, and who is viewing the product from the *outside*, this interdependence is irrelevant and he has the 'right' to use the definition as given by equation (1). The fact that some of the characteristics would be highly stochastic in nature, with large standard deviations, implies that a non-deterministic approach would be more appropriate. This would obscure the essence of the present study and, as is shown in the case study of Part II, would be unnecessary in certain applications.

For illustration purposes the associated vector space will be restricted to a plane ($N = 2$). Such an

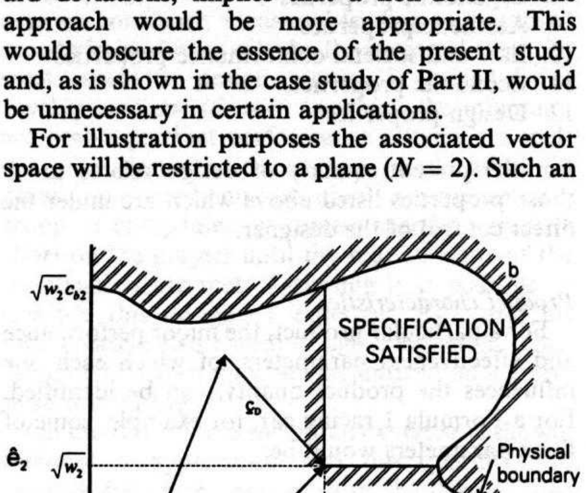

Fig. 6. Product characteristic space.

example is shown in Fig. 6, on which is also shown the limiting physical boundary as discussed above. For the sake of generality it is assumed that this boundary may be influenced by combinations of parameter values and is hence given by an equation of the type:

$$B(C_1, C_2, \ldots, C_N) = 0$$

On the figure are also shown the region in which the specification is satisfied, the specified characteristic vector, $\underline{c}_S$ (where it follows from equation (1) and the definition of w_i that $c_S = 1$) the actual vector $\underline{c}$ and the deficit vector, $\underline{c}_D$.

Relating product quality to product characteristics

The simple case. Suppose we are dealing with a very simple design requirement which demands the satisfaction of a single specified parameter value, e.g. the thermal efficiency, η. From equation (1) the system characteristic vector becomes a scalar of size:

$$c = \eta/\eta_S$$

where η_S = specified thermal efficiency. A sensible definition for quality would in this case be (setting the Carnot efficiency $= \eta_C$):

$$Q = \frac{(c_b - 1)c}{c_b - c} = \begin{cases} 0 & \text{if} \quad c = 0 \\ 1 & \text{if} \quad c = 1 \\ \infty & \text{if} \quad c = c_b = \eta_C/\eta_S \end{cases} \qquad (2)$$

A graphical portrayal of this 'fundamental' relationship between quality and system characteristic is shown in Fig. 7. In the following three sections the general case where more than one system characteristic are important, will be considered.

Quality demands of the stubborn client. In this case it is demanded that the design solution shall satisfy each and every specified design characteristic, i.e.

$$c_i \geqslant 1, \qquad I = 1, N$$

A possible case is depicted in Fig. 8. For certain characteristics the specification will call for a required nominal value and an allowable tolerance. In such cases a simple algebraic function of the inverse of the tolerance could be used as the characteristic. Despite the fact that the size of the actual characteristic vector, c, exceeds that of the one specified, c_S, no credit is given for the over-designed characteristics. In other words, from the client's perspective, $\underline{c}$ and $\underline{c}_{eff}$ are equivalent. As

$$\underline{c}_D = \underline{c}_S - \underline{c}$$

let

$$\underline{c}'_D = \text{pos}\,(\underline{c}_D)$$

(set all negative components of $\underline{c}_D = 0$).

$$\therefore\ \underline{c}' = \underline{c}_S - \underline{c}'_D$$

and

$$c_{eff} = \frac{\underline{c}' \cdot \underline{c}_S}{c_S}$$

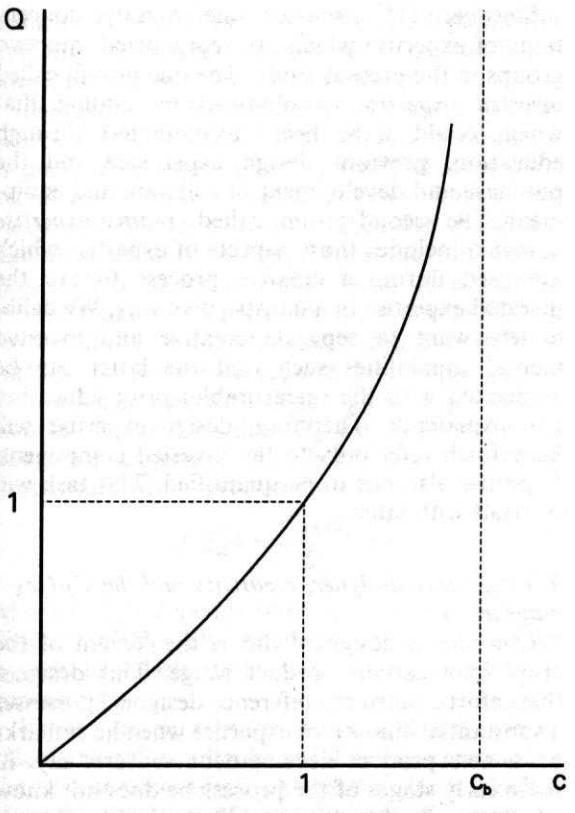

Fig. 7. Fundamental relationship between design quality and system characteristic.

Hence, the equivalent definition of quality could be:

$$Q = \frac{(c_b - 1)c_{eff}}{c_b - c_{eff}} = \begin{cases} 0 & \text{if} \quad c_{eff} = 0 \\ 1 & \text{if} \quad c_{eff} = 1 = c_S \\ \infty & \text{if} \quad c_{eff} = c_b \end{cases} \tag{3}$$

where $\underline{c}_b$ is defined in the figure.

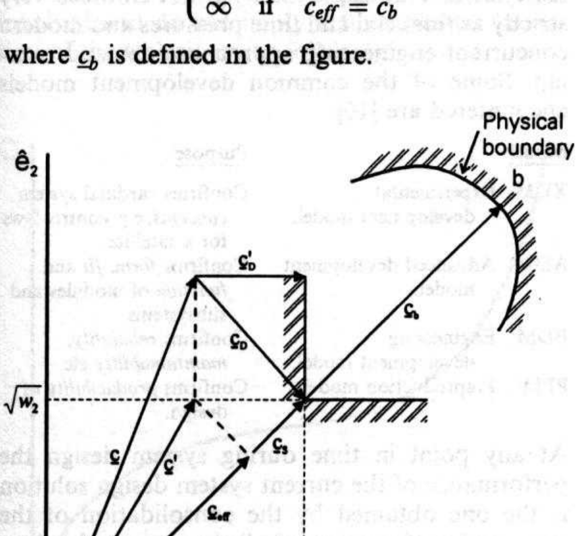

Fig. 8. Effective characteristic vector as seen by a stubborn client.

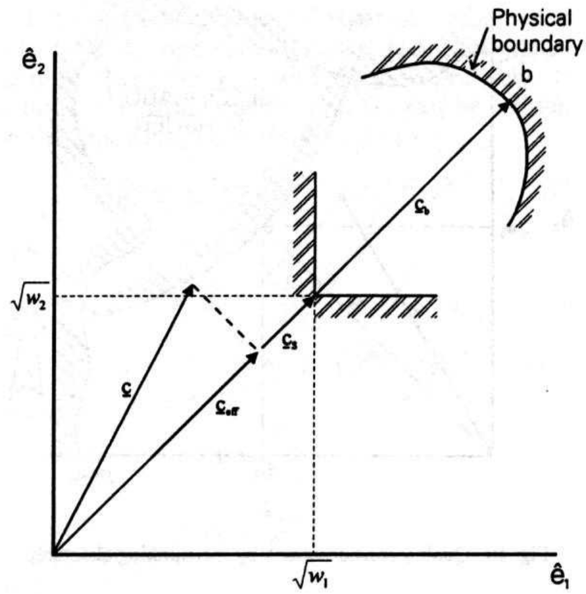

Fig. 9. Effective characteristic vector for an accommodating client.

Quality for the accommodating client. Here the client does give credit for characteristic values which exceed those specified (Fig. 9), though some might still fall short, and the magnitude of the effective characteristic vector is:

$$c_{eff} = \underline{c} \cdot \underline{c}_S / c_S$$

Hence Q can be calculated by means of equation (3).

Quality as assessed by the thinking client. During the design of sophisticated technological products it often happens that at an advanced stage it is found that some of the design requirements are met or exceeded whilst others are not. For example, if the product to be designed is a gas turbine engine for a commuter aircraft and it is found that although the engine is heavier than was specified, the specific fuel consumption turns out to be less than the specified requirement. In such cases the client (in this example, the prime contractor) would consider the effect of deviation from specification on a crucial overall system performance parameter, e.g. the maximum permissible payload or the projected return on investment in the system development. To be able to do this, knowledge of the following functional relationship is required:

$$\begin{aligned} P &= P(c_1, c_2, \ldots, c_N) \\ &= P(\underline{c}) \end{aligned} \tag{4}$$

where P = appropriate system performance parameter.

By means of equation (4), surfaces of constant P can now be calculated and portrayed in the characteristic space, Fig. 10. In this case, a suitable definition for quality would be:

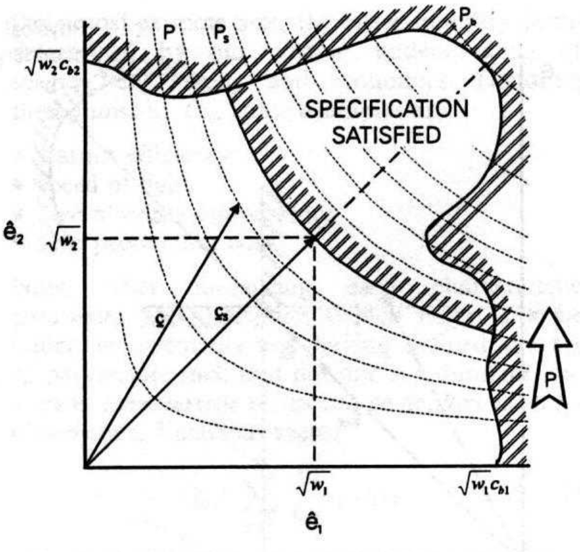

Fig. 10. Quality considerations by the thinking clientship.

$$Q = \frac{(P_b - P_S)P}{P_S(P_b - P)}$$

$$= \begin{cases} 0 & \text{if} \quad P = 0 \\ 1 & \text{if} \quad P = P_S \\ \infty & \text{if} \quad P = P_b \end{cases} \qquad (5)$$

where the symbols are defined in Fig. 10.

It is interesting to note that this latter definition of quality can be interpreted as being equivalent to the preference parameter of Malen and Hancock [13].

Summary

As shown above, it is possible to quantify quality of design. The exact quality model used in each case would have to be established by means of consultation with the client.

EXPERTISE, THE REFERENCE DESIGNER AND CREATIVITY

Expertise is a concept which is currently being warmly debated by a number of disciplines such as computer science, engineering, psychology and philosophy. A thought-provoking set of papers by a group of researchers from these various disciplines has recently collectively appeared in a special issue of the *International Journal of Expert Systems* (Volume 7, number 1, 1994). It is interesting to note that some of these authors treat expertise with a little contempt, e.g. experts having obtained epistemic powerful positions [14] in society and often thriving on 'persuasive bluff'. In the present study the term expertise will strictly relate to a designer's knowledge base which allows him to create a product according to requirements contained in the development specification. The quality of his product is objectively measurable by means of the criteria as discussed in the previous sections ensuring elimination of any form of bluff.

Sternberg [15] discusses nine cognitive conceptions of expertise which are reorganized into two groups in the present study. The one group, called *invested expertise*, is obtained by adding that which could have been accumulated through education, previous design experience and the purchase and development of software and equipment. The second group, called *creative expertise in action* includes those aspects of expertise which are used during a creative process to tap the invested expertise in a constructive way. We deliberately want to separate creative and invested mental capabilities such that the latter can be associated with the (measurable) prior education and experience. Therefore, design expertise will henceforth refer only to the invested component. Expertise also has to be quantified. This task will be dealt with later.

The reference designer, creativity and the $C_E Q e_X$ diagram

Consider a designer who is the 'cream of the crop' in a certain product range. This designer (henceforth called the reference designer) possesses a substantial amount of expertise when he embarks on a new product development venture, say. In these early stages of the process he does not know what the final solution will look like but if sound systems engineering practice is followed, the current design will evolve, step by step, towards a $Q = 1$ solution. This systematic evolution for complex systems is usually done by proposing, analyzing, building, testing and modifying suitable models (=prototypes, in layman's language); to sequentially confirm the conceptual, the form, fit and function and the engineering (e.g. reliability, maintainability and producibility) characteristics of the system. This sequentiality is not enforced very strictly as financial and time pressures and modern concurrent engineering approaches demand overlap. Some of the common development models encountered are [16]:

Model	Purpose
XDM: Experimental development model.	Confirms cardinal system *concepts*, e.g. control laws for a satellite.
ADM: Advanced development model.	Confirms *form, fit* and *function* of modules and subsystems.
EDM: Engineering development model.	Confirms *reliability*, *maintainability* etc.
PPM: Preproduction model.	Confirms *producibility* of design.

At any point in time during system design the performance of the current system design solution is the one obtained by the consolidation of the measured performance of all the various development models under test. The current system characteristic vector can hence be constructed based upon only those system characteristics which have been confirmed by measurement. The associated product quality, Q, will therefore normally gradually increase as the system development process absorbs *creative effort* (C_E), the latter parameter implying the measurable number of person-hours which have been spent on the project.

The expected dependence of C_E upon Q is as shown in Fig. 11. Even for an adaptive redesign, it is possible to express the system's characteristic vector in such a way that Q will start from a zero value (see the case study in Part II). A certain minimum threshold value of C_E is required before Q will become measurable. Now, it is fair to assume that as Q increases to values corresponding to the limits of the designer's creative abilities, further increases will require increasing C_E, or $\mathrm{d}C_E/\mathrm{d}Q$ increases with Q at high Q, Fig. 11. It is also fair to assume that C_E will depend on the designer's expertise, E_X, hence, the following functional form is proposed:

$$C_E(Q, E_X) = \frac{C_E(Q)}{E_X} g(E_X) \tag{6}$$

where $C_E(Q)$ depends only on Q and $g(E_X)$ is a function of E_X only, which allows for other than hyperbolic relationships between C_E and E_X for constant Q.

For the present it will be assumed that E_X can be calculated independently and, like C_E, expressed in the unit of person-year. A creative effort which is given by equation (6) will be termed a *uniform effort* and for the moment the study will be restricted to such cases with the further assumption that

$$C_E(Q) = \Gamma_0 + \Gamma_1 Q^m + \Gamma_2 Q^n \tag{7}$$

where Γ_0, Γ_1, Γ_2, m and n are constants and $0 < m < 1$ and $n > 1$. This particular mathematical form is chosen as it models the trend suggested in Fig. 11. These restrictions are only introduced to compactly illustrate the concepts involved and do not imply a fundamental limitation of the techniques to follow.

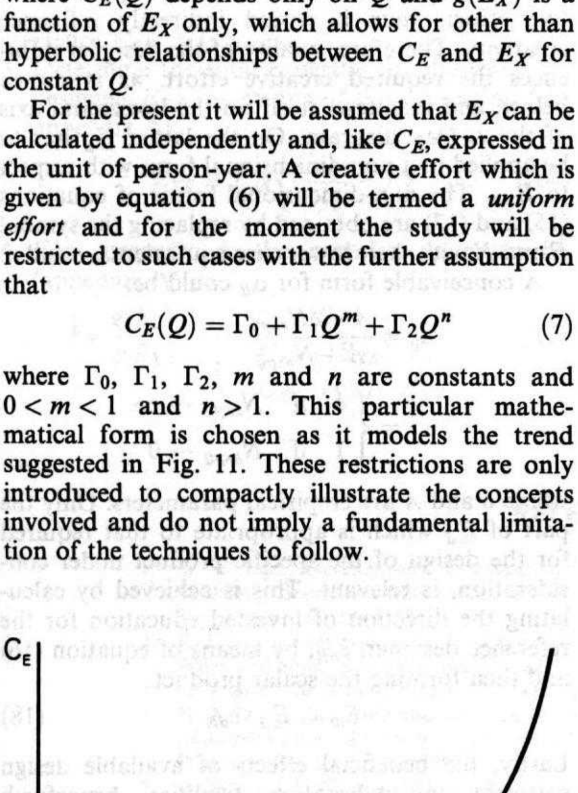

Fig. 11. Anticipated creative effort vs quality relationship.

Let the specific values of expertise and creative effort for the reference designer under consideration be given by E_{XR} and C_{ER}, respectively. It follows that equations (6) and (7) can be written in the following dimensionless forms:

$$c_E(Q, e_X) = \frac{c_E(Q)}{e_X} g(e_X, E_{XR}) \tag{8}$$

and

$$c_E(Q) = \frac{C_E(Q)}{E_{XR}^2}$$

$$= \gamma_0 + \gamma_1 Q^m + \gamma_2 Q^n \tag{9}$$

where

$$e_X = \frac{E_X}{E_{XR}}$$

$$c_E = \frac{C_E}{E_{XR}}$$

and

$$\gamma_i = \frac{\Gamma_i}{E_{XR}^2}, \quad i = 0, 1, 2$$

The concept *creativity* has to be introduced now. Consider a company with initial expertise E_X that has spent a total creative effort C_E to produce a product of quality Q. It sounds logical that creativity should be defined such that it will be larger for a larger Q and smaller for a larger E_X or a larger C_E, hence, creativity (c_r) is defined as:

$$c_r = \frac{K_Q Q g(E_X)}{E_X C_E}$$

$$= \frac{k_Q Q}{e_X c_E'} \tag{10}$$

where K_Q = a function of Q (see below),

$$k_Q = \frac{K_Q}{E_{XR}^2}$$

and

$$c_E' = \frac{C_E}{g(E_X) E_{XR}}$$

$$= \frac{c_E(Q)}{e_X} \tag{11}$$

by means of equations (6) and (9).

The rationale behind equation (10) is the Oxford definition of creativity which was given earlier. According to this equation, less E_X or less C_E would imply a higher creativity (for the same Q), which is in line with the idea of 'forming out of nothing (or little)'. We now calibrate creativity by assuming that, for the reference designer, c_r = 1. Although another designer may possess less (or more) expertise in comparison, it is assumed (for the moment) that he or she is inherently just as creative. Thus, setting $c_r = 1$ in equation (10) leaves:

$$e_X = \frac{k_Q Q}{c_E'} \tag{12}$$

which is a hyperbolic relationship for a fixed value of Q. Note that for any hyperbola there exists an associated, constant area, which in this case is:

$$A(Q) = k_Q Q = c'_E e_X \quad (13)$$

Equation (13) is used to solve for k_Q by setting:

$$A(Q) = c'_{ER} e_{XR} = \gamma_0 + \gamma_1 Q^m + \gamma_2 Q^n \quad (14)$$

by means of equations (9) and (11).

$$\therefore\ k_Q = \frac{\gamma_0}{Q} + \gamma_1 Q^{m-1} + \gamma_2 Q^{n-1} \quad \text{if } Q > 0$$

Equation (12) is in essence the $c_E Q e_X$ diagram, as was introduced earlier, which can simply be constructed by choosing values for Q and drawing the corresponding hyperbolas. On a log-log scale, constant Q lines will become straight. Application of equation (10) to establish the creativity of other than reference designers, will be demonstrated in Part II.

In summary then, the reference designer is per definition one with creativity and specific expertise of value unity and one who follows a uniform creative effort.

Quantifying design expertise

It follows from the previous discussions that the invested expertise of a designer will depend on a host of factors such as the number of design team members, the educational and practical background of each, the available computational and experimental facilities and the appropriateness of all these with regard to the type of product to be designed. As was the case with the quantification of quality, a rigid law for the quantification of expertise does not exist but an approach which is compatible with the present considerations will be followed here.

Firstly an estimation of the *invested education* contained in the design team is to be made. Suppose there are n_D different engineering disciplines represented, with a total number of n_{mi}, $i = 1, n_D$, team members belonging to each one. Suppose further a member number j in group i has had N_{edij} and N_{expij} years of formal tertiary education and practical experience, respectively. The following definition of the invested education vector is now proposed:

$$\underline{E}_d = \sum_{i=1}^{n_D} \sum_{j=1}^{n_{mi}} \alpha_{ij} \beta_{ij} N_{edij} \hat{e}_d \quad (15)$$

where

α_{ij} = experience amplification factor,
β_{ij} = adjustment factor for redundancy or amplification between members,
$\hat{e}_d$ = unit vector depicting collective direction of education vector, i.e.

$$\hat{e}_d = \frac{\sum_{i=1}^{n_D} E_{di} \hat{e}_i}{\sqrt{\sum_{i=1}^{n_D} E_{di}^2}} \quad (16)$$

where

$$E_{di} = \sum_{j=1}^{n_{mi}} \alpha_{ij} \beta_{ij} N_{edij} \quad (17)$$

and $\hat{e}_i$ = base unit vector for discipline i.

It should be noted that $\underline{E}_d$ represents quantity and not quality. The temptation to adjust β_{ij} according to individual competence should therefore be resisted. $\underline{E}_d$ is only used to help establish the invested expertise. In the present *from the outside* view of creativity, it is assumed that increased competence would reduce required creative effort, thus it would indirectly influence creativity. Therefore, quality of the designer influences the required creative effort, as is shown below, and manifests itself on the horizontal axis of the $c_E Q e_X$ diagram. On the latter, $\underline{E}_d$ has to be applied in a non-dimensional form with respect to E_{XR}. The non-dimensional forms of equations (15) and (17) are obtained by replacing the symbol E and N with their lower case equivalents, e and n.

A conceivable form for α_{ij} could be:

$$\alpha_{ij} = \frac{A + \delta N_{expij}}{A + N_{expij}} = \begin{cases} \delta & \text{if } N_{expij} \to \infty \\ 1 & \text{if } N_{expij} \to 0 \end{cases}$$

where δ and A are empirical parameters. Only the part of $\underline{E}_d$ which is appropriate to that required for the design of the specific product under consideration, is relevant. This is achieved by calculating the direction of invested education for the reference designer, $\hat{e}_{dR}$, by means of equation (16) and then forming the scalar product:

$$E_{dr} = \underline{E}_d \cdot \hat{e}_{dR} \quad (18)$$

Lastly, the beneficial effects of available design software and laboratory facilities, henceforth referred to as *facilities*, must be incorporated. This is done by following four steps.

1. Calculate the person-year 'equivalent' of the facility, C_{EF}, which is obtained by dividing the hiring or purchase cost of the available facility by the engineering person-year rate, assuming $c_r = 1$. The purchase cost of a facility is included in C_{EF} in the event where this facility is acquired solely for the particular project.
2. As was done in equation (15), form a multidimensional *facility space* for both the company under consideration (company A, say) and the reference designer and establish the relevant contribution, C_{EFr}, by a scalar product similar

to equation (18). For the reference designer, therefore:

$$\underline{C}_{EFR} = \sum_{k=1}^{n_D} \sum_{l=1}^{n_{fk}} \beta_{kl} C_{EFkl} \hat{e}_{fR}$$

where

C_{EFR} = creative effort required to access all facilities,

n_{fk} = number of facilities per discipline,

C_{EFkl} = Creative effort required to access facility number kl,

$$C_{EFk} = \sum_{l=1}^{n_{fk}} \beta_{kl} C_{EFkl}$$

and

$$\hat{e}_{fR} = \frac{\sum_{k=1}^{n_D} C_{EFk} \hat{e}_k}{\sqrt{\sum_{k=1}^{n_D} C_{EFk}^2}}$$

Hence $C_{EFr} = \underline{C}_{EF} \cdot \hat{e}_{fR}$.

3. Determine the total expertise for the reference designer, E_{XR}, by means of the expression (see appendix A):

$$E_{XR} = E_{dR}\left\{\frac{C_{EFR}}{C_{ER}} + 1\right\} \quad \text{(A4)}$$

4. For company A the expertise is given by (appendix A):

$$E_X \frac{g(E_d)}{g(E_X)} = \frac{E_d}{1 - \dfrac{C_{EF}}{C_{ER}} \dfrac{g(E_{XR})}{g(E_d)} \dfrac{E_d}{E_{XR}}} \quad \text{(A6)}$$

CONCLUSIONS

In this paper definitions for product design quality, designer expertise and creative effort have been introduced in a quantified manner such that they are interrelated and can be graphically depicted as a set of hyperbolic curves, the $c_E Qe_X$ diagram. Product design quality Q is mathematically related to the product characteristics in such a manner that $Q = 0$ at design inception, $Q = 1$ when the requirements of the development specification are met and $Q \to \infty$ when characteristics approach physical boundaries. Designer expertise is expressed in person-years and includes all the invested tertiary education and relevant experience contained in the design team, as well as investment in design software and laboratory facilities.

The notion of a reference designer, whose performance is used for the calibration of the $c_E Qe_X$ diagram of a product type, is introduced. For a reference designer, the functional relationship between expertise, creative effort (C_E) and quality is defined such that creativity is always unity and effort is always uniform with respect to Q.

In Part II it is shown how the performance of other designers can be traced as C_E vs Q data points rendering a creative path. The creativity of such designers can be obtained by calculating the ratio of appropriate areas on the diagram.

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APPENDIX A: CONSTRUCTION OF THE $c_E Q e_X$ DIAGRAM

In order to be able to construct a $c_E Q e_X$ diagram, the following data are required:

- For the reference designer, E_{dR} and C_{EFR}.
- For the reference designer, data of C_E vs Q.
- For a series of other designers (each with $c_r = 1$), covering a variety of educational levels, data of C_E vs E_d for $Q = 1$. The quantity C_E is to include C_{EF}.

For a candidate designer, the expertise level E_X can be obtained by assuming that $c_r = 1$ and that the (C_E, E_X) co-ordinates of points A, B and C of Fig. 12 are respectively given by:

$$(C_{ER}, E_{XR}), (C_{ED} + C_{ER}, E_X) \quad \text{and} \quad (C_{EF} + C_{ED} + C_{ER}, E_d)$$

where C_{ED} is at yet an unknown function of E_d and C_{EF}, and E_{XR} is also yet unknown. Hence, from equation (11):

$$a = \frac{C_{ER}}{g(E_{XR})E_{XR}}$$

$$c = \frac{C_{ED} + C_{ER}}{g(E_X)E_{XR}} \tag{A1}$$

$$\text{and } d = \frac{C_{EF} + C_{ED} + C_{ER}}{g(E_d)E_{XR}}$$

With reference to Fig. 12, equality of areas requires that:

$$a = e_d \cdot d \tag{A2}$$

From equations (A1) and (A2) it follows that C_{ED} is given by:

$$\frac{C_{ED}}{C_{ER}} = \frac{E_{XR}}{E_d}\frac{g(E_d)}{g(E_{XR})} - \frac{C_{EF}}{C_{ER}} - 1 \tag{A3}$$

For the reference designer $C_{ED} = 0$. Thus, equation (A3) gives, for this case:

$$E_{XR} = E_{dR}\left\{\frac{C_{EFR}}{C_{ER}} + 1\right\}\frac{g(E_{XR})}{g(E_{dR})} \tag{A4}$$

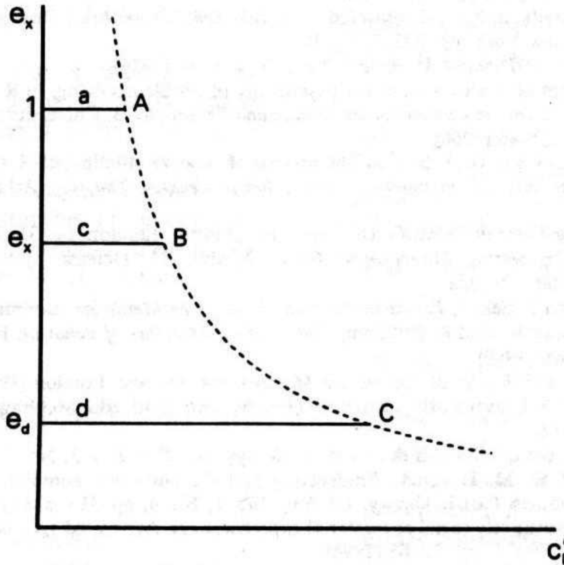

Fig. 12. Construction of $c_E Q e_X$.

Two calibrating assumptions are introduced:

$$g(E_{dR}) = 1$$

and

$$g(E_{XR}) = 1$$

which allows E_{XR} to be calculated from equation (A4). Equations (11), (A1) and (A2), give:

$$g(E_d) = \frac{E_d C_E}{C_{ER} E_{XR}} \tag{A5}$$

By using equation (A5) and the data, the function $g(E_d)$ can thus be calculated for $0 < E_d \leqslant E_{dR}$. The constants Γ_0, Γ_1, Γ_2, m and n can be obtained experimentally from the C_E vs Q data for the reference designer by applying equations (6) and (7):

$$C_E = \frac{\Gamma_0 + \Gamma_1 Q^m + \Gamma_2 Q^n}{E_{XR}}$$

to a number of the data points and obtaining the unknown constants by means of a curve-fitting technique such as least-squares.

As $e_X \cdot c = e_d \cdot d$ (Fig. 12), equations (A1) and (A3) can be used to implicitly solve for E_X:

$$E_X \frac{g(E_d)}{g(E_X)} = \frac{E_d}{1 - \dfrac{C_{EF}}{C_{ER}} \dfrac{g(E_{XR})}{g(E_d)} \dfrac{E_d}{E_{XR}}} \tag{A6}$$

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