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A framework for the assessment of the creativity of product design teams

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A generic approach for the measurement of technological creativity is presented. This method, referred to as the REV (resources, effort, value) technique, holds promise for the assessment of the creativity of either individuals or teams cooperating in new product development, duly considering the benefits of support infrastructure. The output of the creative process is a quantity called *design value*, the measurement of which is permitted by the phenomenon that invention always manifests itself by means of measurable value parameters. The inputs to the creative process are the creator's *resources* and the amount of *effort* spent on the project. Effort is represented by the cumulative labour-months and materials consumed by the development process, and resources are a measure of external support, team size, education and experience level, and development facilities used. Creativity is defined as the relative efficiency of design value generation. An application of the methodology in the field of technology transfer is given.

Keywords: Creativity assessment; Rating design teams

1. Introduction

In new product development (NPD), it is generally accepted that business success is influenced by the creativity of the development team. For the computer industry, Loch *et al.* (1996) found that design quality positively correlates with sales growth, suggested to be driven by the creativity and skills of the design team. Competitive advantage is not obtained by merely pouring more money into research and development (R&D), but success is rather related to more efficient NPD. Studying 267 early-stage NPD projects in the chemical industry, Stevens *et al.* (1999) found positive correlations between profits resulting from NPD project analysis and the degree of creativity of the analysts evaluating those projects. A number of studies have shown that the primary reason for new product failure is the lack of new product uniqueness (Crawford 1977, Cooper and Kleinschmidt 1990, Cooper 1993). The ability to assess the creativity of individual designers and development teams is hence of importance.

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Psychologists distinguish between creativity as a *trait* and creativity as an *achievement*. Eysenck (1994) defines creativity as a trait as a dispositional characteristic of an individual leading them to produce acts, items and instances of private novelty, while creativity as an achievement relates to the ability to actually produce works that are novel in the public sense. Many methods for the assessment of creativity exist. Hovecar and Bachelor (1989) mention that the measurement of creativity as a trait usually relies on the detection of *divergent* thinking or *fluency*. Eysenck (1994) has revealed a relationship between psychotism and creativity, permitting the testing for the latter by means of tests for *overinclusion* (the inability to maintain conceptual boundaries). Proper manipulation of the Myers-Briggs Type Indicator (Myers Briggs and McCaully 1985) scores indicates latent creative abilities of subjects (Gough 1981). Gough developed the Myers-Briggs Type Indicator Creativity Index, which was used as an assessment tool by Stevens *et al.* in the study mentioned earlier. According to a number of proposed models, creativity as an achievement is domain dependent and it is linked to various cognitive, personality and environmental variables. For example, Sternberg and Lubart (1991) synthesized a six-component 'investment' model in which the creative 'resources' are intelligence, knowledge, intellectual style, personality, motivation and the environment, and the 'output' is the created product. Various researchers have indicated that historic *eminence* is a reliable and valid measure of creativity as an achievement. A number of illuminating experiments have been conducted at the Berkeley Institute of Personality Assessment and Research throughout the years. One of these research projects entailed assessing the validity of different divergent thinking tests by using, as subjects, 100 captains in the US Air Force. Studying a sample of 129 architects, another project demonstrated the validity of the Barron–Welsh Art Scale for indicating creativity as an achievement.

Technological creativity and invention have been widely investigated, and measures for these two (and other related) phenomena have been proposed. For example, Gilman (1992) defines *inventivity* as the number of man-hours, or dollars, needed to produce the average invention. White (1982) proposed determinants of success of invention in both technology and business contexts. Technological criteria include constraints added and removed by the invention, and its capacity to stand-alone. Business criteria include changes in existing operations and requirements for new ones, and whether the innovation provides market expansion or lower price. Altshuller (1984) views invention as the discovery and removal of contradictions, and he defines five levels of invention, where higher levels are associated with increasing degree of difficulty and increasing degree of change of an object and its environment. The Altshuller philosophy is based on the analysis of thousands of registered patents. The insights gained from this process led to the formulation of the *Theory of Solving Inventive Problems* (referred to by the Russian acronym TRIZ), which is an algorithmic approach to solving technical problems (Altshuller 1996). For the design of engineering systems, Moody *et al.* (1997) measure *design difficulty* by combining the effects of factors such as the design type, the complexity of knowledge required, the number of major subsystems, quality requirements, manufacturing process design and unit sales price requirements. Due to the fact that a high score for design difficulty implies numerous contradictions to be resolved, the similarity between design difficulty and invention in the Altshuller sense is apparent. Wilbur *et al.* (1995) discuss a vast number of *metrics* used to assess the effectiveness and efficiency of the development process. These metrics are usually divided into the categories of process, progress and product. Related to Sternberg and Lubart's investment view of creativity, Redelinghuys (1997a, 1997b) proposed a framework, called the $c_E Qe_X$ technique, intended for the assessment of the creativity of students or designers, working either individually or in collaboration as a team. Later, the same author summarized criteria for the detection of *invention gain* in engineering design (Redelinghuys 2000a, 2000b). Various measures for changes in economic and productivity efficiency due to innovation are widely used. However, due to the fundamental difference between invention and innovation (Redelinghuys 2000a), these measures are presently not considered.

In the present study a framework for the assessment of the creativity of NPD teams is introduced. This framework, referred to as the REV (resources, effort, value) technique, is closely associated with the $c_E Q e_X$ approach. The crux of the method is an *external view* of creativity (i.e. viewing only inputs and outputs of the process). This view corresponds to that taken by economists viewing human actions and resembles the thinking of Sternberg and Lubart and of Gilman mentioned earlier. In the next section, a brief introduction to the REV technique as well as a quantified definition of creativity are given. The existence of the REV nomogram is substantiated by means of a case study, in which project planning data are suitably transformed. This is followed by discussions of concepts such as design value, effort and resources. Mathematical procedures for the quantification of the latter three concepts are proposed. Finally, application of the technique is demonstrated in the field of technology transfer.

2. The REV technique

The $c_E Q e_X$ technique (Redelinghuys 1997a, 1997b), which in adapted form will here be referred to as the REV (resources–effort–value) technique, is the proposed unifying model for the assessment of technological creativity. The technique relies on constructing a composite graph of *resources* versus *effort expended* for various values of *added design value* (figure 1). Resources, called *expertise* by Redelinghuys (1997a, 1997b) are a measure of external support, team size, education and experience level, and development facilities used. Effort is represented by the cumulative labour-months and materials consumed by the design process. As shown in the next section, design value is defined such that it equals zero at project start and one when the design has been validated and verified, respectively. Figure 1, which acts as a nomogram for creativity analysis, is the design-process equivalent of the well-known *production function* diagram used by production engineers and economists, in which loci of constant production quantities are plotted for labour on the abscissa and capital on the ordinate (*e.g.* as explained

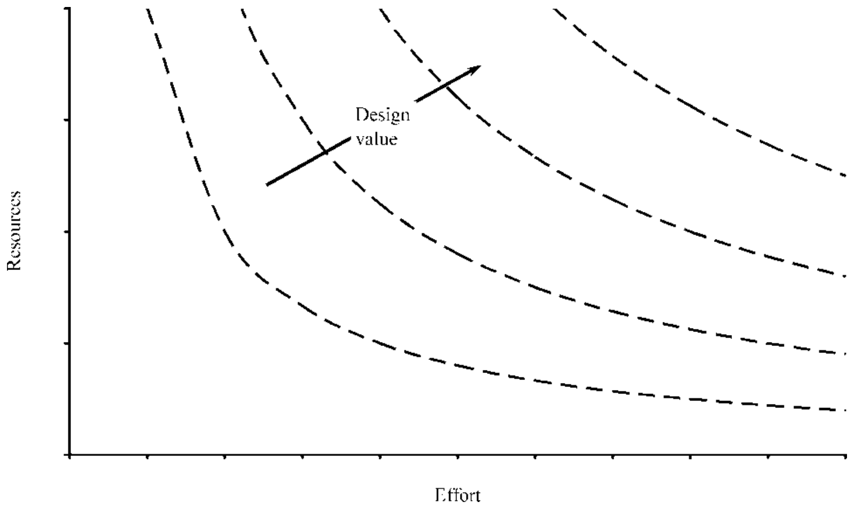

Figure 1. Resources–effort–value nomogram.

in Rosegger 1997). Further justification for the existence of the REV nomogram in product development is given by means of a case study in appendix A.

In order to perform a creativity assessment, three parties are needed: a *subject* (the candidate designer, who might be an individual or a team), an *assessor* (*e.g.* a program manager or a reviewing body) and a *reference designer* (*e.g.* an actual or imagined master designer in the particular domain). At the start of the creative process the subject has to be fully aware of the specified requirements for the device to be designed. The assessor has to be familiar with both the particular technological field and the capabilities of the reference designer. The effort that the reference designer would require to achieve a certain design value would depend on the resources at his disposal. The smaller the available resources, the more effort would be required, and vice versa. Thus the assessor could estimate, for the reference designer, the relationship between the resources required to achieve a particular design value and the effort expended. This allows the REV nomogram to be constructed by plotting, for the reference designer, required resource levels against effort for various values of specified value, leading to isovals shown as dashed lines on figure 1. As an example, and simplified for illustration purposes, measurement of creativity during system design proceeds as follows. As the project progresses, the assessor monitors the resources utilized and the effort expended by the subject creator. Imagining that the reference designer is conducting the design, plotting the monitored data set as coordinates on the nomogram produces a *reference creative path* (figure 2). A rising path is shown because the design team size and the extent of support facilities utilized normally grow as the project gains momentum. In general, after having devoted an equal amount of effort towards the design and having equal access to resources, the subject would achieve a lower added design value than the reference designer. This is due to imperfections such as requirement instability, process inefficiencies and designer shortcomings. But it is possible for a highly creative subject, by adding design value through invention, to exceed the reference design value. Plotting achieved value versus effort on the nomogram allows the construction of the *achieved creative path*. The quantity R_r on the ordinate of figure 2 now represents the *potential* resources, and it will be less than R due to the low added design value in the general case. Defining creativity in engineering design as *the relative efficiency of design value generation* (appendix B), the subject's creativity, after having expended E units of effort, would be represented by the quotient R_r/R.

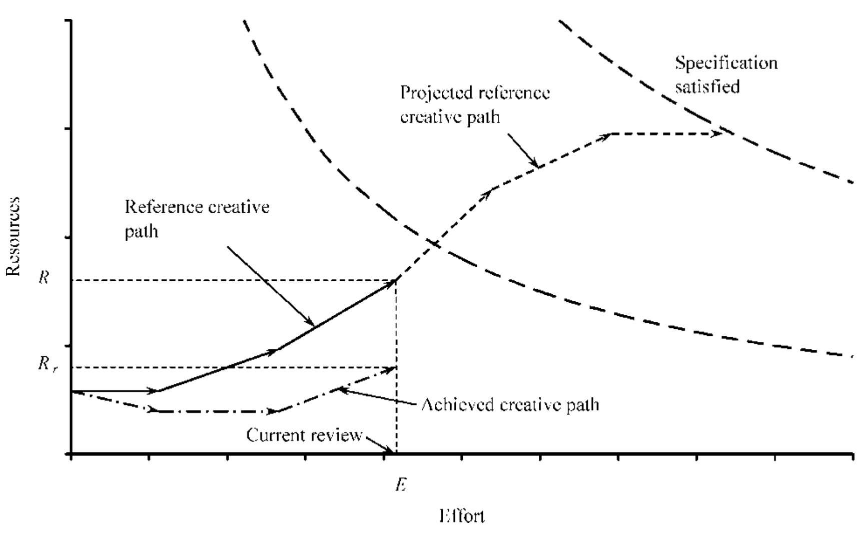

Figure 2. Relative creative performance.

3. Design value

In engineering design, value and quality are often seen as synonymous concepts. The literature contains many definitions for product quality. *Design for quality* and the *measurement of quality conformance* during production are often referred to as *off-line* and *on-line* quality control, respectively. The present study deals with off-line quality control only, for which various quantified definitions have seen the light and are regularly used by design engineers, especially to assist choosing between different solution concepts (for example, see Pahl and Beitz 1996). These methods traditionally entail the selection of criteria, the choice of scales for the criteria, the determination of values for the criteria and, finally, the processing of the individual values into a total value. A modern and influential definition of design quality is the one formulated by Taguchi (1986). According to Taguchi, the quality of a product is the (avoidance of) loss imparted to society (other than losses incurred by its intrinsic function) from the moment the product is shipped.

Design value can be viewed as consisting of two contributions: one due to state-of-the-art (or routine) design, and another due to added value resulting from invention. This latter component, added design value (referred to as a differential contribution by Redelinghuys 2000a, 2000b), implies an original knowledge contribution to design science (Eder 1996; Hubka and Eder 1996). Careful analyses of historically significant inventions have revealed that each can be linked to a prior network of mature products leading to the invention in question, a phenomenon Dasgupta (1996) calls *the phylogeny law*:

> Every act of invention or design has a phylogenic history.

In the REV technique, design value is defined such that it will equal zero and one when the design is started and when the design goals are reached, respectively. The value at the start of the design process, which is to be subtracted from any subsequent value assessment, is hence determined by the value characteristics of the intended product's phylogenic predecessors. Redelinghuys (2000a) formulated the following proposition for sensing invention as a gain in design value:

> The invention of a technical system manifests itself as at least one added, removed or changed system parameter (which implies a differential value contribution to the investor, the producer, the consumer/user and/or society) with respect to the system's phylogenic predecessor(s).

In engineering design, various models for the quantification of design value could be contemplated. Two classes of value models are recommended for REV studies. The first model relies on the established *earned value* assessment technique as used in project management (for example, Burke 1992). This somewhat indirect method is relatively easy to apply as it relies on using standard planning and progress review data. The method is indirect as added value is judged by consideration of the state of completion of planned activities, and not via simulation of product properties. The second class relies on *value engineering* models (for example, Cross 2000), focusing directly on product functional values and aims to increase the difference between the cost and value of a product. Simulations of expected product properties and costs are performed, but predictions can be unreliable due to requirement validation and design verification difficulties. An appropriate value engineering model could be based on the following approach:

1. The design is structured into phases; for example, conceptual design, preliminary design and detail design, as presented by Blanchard and Fabrycky (1998). The primary objective

of each phase is the generation of 'product knowledge'; for example, data contained in a system specification and development and product specifications. Various sorts of data make up product knowledge. In the early phases, design requirements form an important data sort.

2. The product knowledge grows during each design phase. Early in the particular design phase, the Chief Systems Engineer needs to prioritize the characteristics that dominate product value. As the design process proceeds, parameter values will be allocated to a number of the characteristics.
3. System parameters may be of various types; for example, larger-the-better, smaller-the-better, nominal-the-best, operating window and fractional (Belavendram 1995). All parameters are to be mathematically transformed to the larger-the-better type. Let ρ_i be a typical transformed parameter belonging to the design space.
4. The Chief Systems Engineer needs *value models* that are written in functional form as $V = V(\rho_1, \rho_2, \ldots, \rho_N)$, where N is the number of parameters belonging to a particular system characteristic.
5. To each of the allocated parameters ρ_i the design team is to allocate two time dependent variables; that is, V_{vali} and V_{veri}, where V_{vali} is the reliability of validation and V_{veri} is a quality of verification factor. Both these quantities will fall between zero and one. It follows that the *value parameter* $q_i = V_{\mathrm{vali}} \times V_{\mathrm{veri}}$ will equal zero and one at the start and the end of the phase, respectively.
6. The created value (or quality) associated with a system characteristic, at any point in time, is hence given by:
$$V = V(q_1\rho_1, q_2\rho_2, \ldots, q_N\rho_N) \tag{1}$$
7. The variable V_{vali} is influenced by the integrity of validation and by the stability of requirements. V_{veri}, on the other hand, represents the possibility to satisfy requirement ρ_i through design work with the current state of the art. V_{veri} is hence associated with established Technical Performance Measurement (as presented by Wilbur *et al.* 1995).

4. Resources

To be creative while in the process of NPD, substantial amounts of human skill and development facilities are required. Van Wyk (1996) views this 'set of means', or 'created capability', as *technology*, and this author proceeds to describe a *technological entity* as a 'complex cluster of hardware, algorithm and human skills'.

Concentrating on human skills first, the discipline devoted to knowledge – *epistemology* – is a very old one. The nature of human knowledge has been a central subject for speculation by philosophers for many centuries (Magee 1987), and recorded views on the matter date back to Socrates (469–399 BC). Numerous modern attempts at describing and structuring technological knowledge have seen the light. Dasgupta (1996) sees technological knowledge as consisting of basic sciences, mathematics, engineering sciences and *operational principles*. These principles are 'propositions, rules, procedures, or conceptual frames of reference about artifactual properties or characteristics that facilitate action for the creation, manipulation, and modification of artifactual forms and their implementations'.

Eder (1996) describes *design science* as a system of logically categorized knowledge about and for designing. Design knowledge is seen to be a conglomeration of knowledge of the engineering sciences; production methods; procedures, methods and techniques for designing; representation techniques; organizational and administrative techniques; working means and tools; standards, codes, regulations and patents; markets, state-of-the-art and related fields; and relevant experience. The position and area of each statement that contributes to design science can be plotted on the map shown in figure 3. The left-hand and right-hand sides of this figure represent knowledge of technical systems and design processes, respectively, and the vertical axes allow distinguishing between descriptive (theoretical) and prescriptive (factual and methodological) statements. A universal classification and categorization of technical systems is given by Hubka and Eder (1988). The classification is achieved either by function, action principles, degree of complexity, manufacturing similarity, difficulty of designing, degree of standardization, design originality, production type, degree of abstraction, type of operand, application in the technical process or quality. Many descriptions of the design process as followed by individual or collaborating designers are discussed in the literature. Roozenburg and Eekels (1996) give a comprehensive account of the basic design cycle, which is shown in figure 4. This diagram implies that creativity and knowledge resources are inseparable, as two of the actions shown, synthesis and simulation, demand extensive domain-related knowledge.

Concerning the total suite of van Wyk's 'created capability', the empowering effects of development facilities in the form of relevant algorithm and hardware are to be included in knowledge resource descriptions and classifications. For the description of technologies, de Wet (1992) proposes a standard format that distinguishes between function, principle of operation, level of performance, structure, material and size. This approach is compatible with that of Hubka and Eder as discussed earlier. A suggested standardized description of function relies on one verb (processing, transporting and storing) and one noun (matter, energy and information), leading to a nine-cell description of technologies. A wind tunnel, for example, might be classified as an information processor, as the input to and output of wind tunnel testing are a description of a model and a set of aerodynamic measurements, respectively.

The functions of design team personnel might also be easily classified according to the nine-cell scheme.

From the earlier brief discussion, it follows that a designer's knowledge resources are a complex entity unamenable to precise description. Hence attempts at quantifying this nebulous

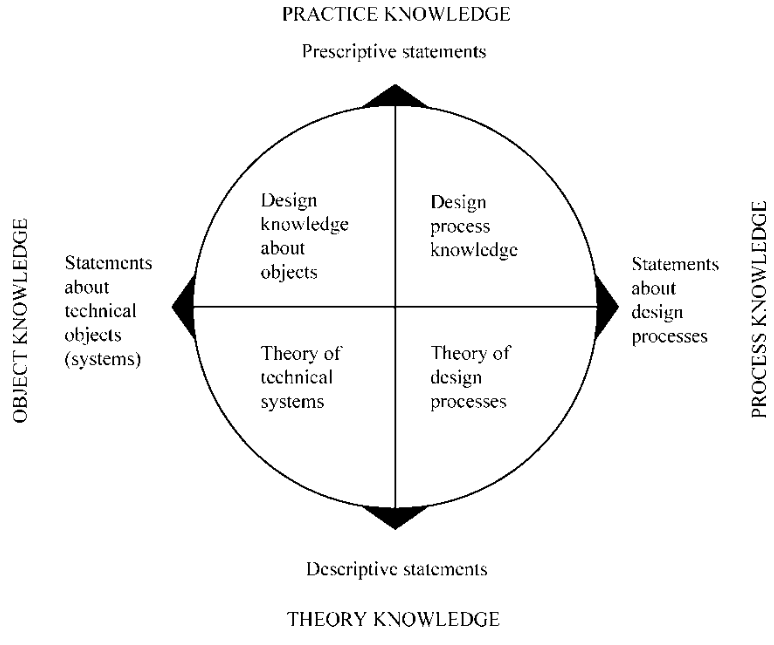

Figure 3. Classes of engineering design knowledge (Eder 1996).

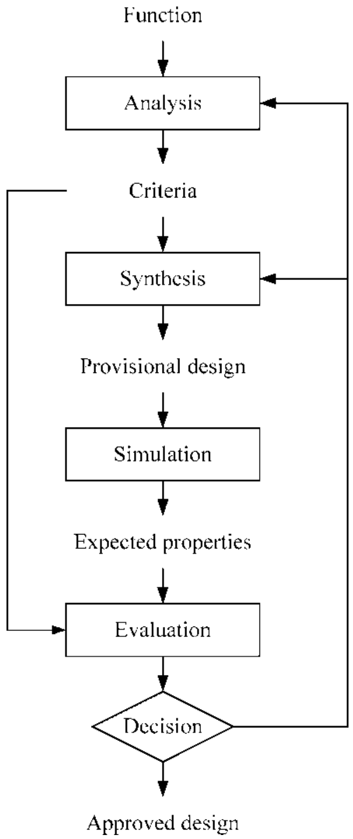

Figure 4. The basic design cycle (Roozenburg and Eekels 1996).

reserve might seem daunting. However, if one decides to describe knowledge resources in terms of formal investment in hardware, software, education and training, rather than in terms of their exact description, the problem is considerably alleviated. It might be objected that the investment view of knowledge would fail to distinguish between the possible different ability of designers to apply their education and development facilities. However, defining creativity as an efficiency, as is done in the REV technique, allows the difference in capabilities of these designers to be detected by differences of their achieved value added to design.

Reported studies based on the quantified investment approach to knowledge resources may be found in the field of cost–benefit analysis and economics. A study by Hsiao *et al.* (1988), as reported in Brent (1996), is of relevance. These authors devised a resource-based pricing scheme for the US system for compensating physicians supplying services for the elderly. Resource costs were divided into four elements:

(i) The time devoted to a service.
(ii) The work intensity demanded by a service. The product of elements (i) and (ii) is called total work (*TW*).
(iii) Relative practice costs (*RPC*). Practice costs relative to gross earnings for each specialty was the index.
(iv) Amortized value for the opportunity cost of specialized training (*AST*). These costs (training and forgone earnings) were spread over the career lifetimes of physicians.

These four elements were combined into a *resource-based relative value* (*RBRV*), as follows:

$$RBRV = TW[(1 + RPC)(1 + AST)]$$

Viewing the product contained in the square brackets as knowledge resources, it is interesting to note that this equation predicts a hyperbolic relationship between work and knowledge resources, as is suggested by figure 1.

Although intended for use in engineering production, rather than in invention, the celebrated Cobb–Douglas production function as used by economists (as discussed, for example, by Gujarati 1995) has been modified by Braunerhjelm (2000) to include the innovative effects of knowledge capital. Knowledge capital is defined as 'accumulated assets in R&D, marketing, software and education', and is comparable with the present potential knowledge resources. Although these established functional forms provide a way for quantifying knowledge resources, they are not suitable for use in creativity assessment (see appendix B).

An approach for the quantification of resources and effort for technological creativity assessment will now be proposed. The present treatment is more concise than that put forward earlier by Redelinghuys (1997a). It will be assumed that, during NPD, the expected value of the (as yet only partially defined) product V will depend on the available capabilities, the efficiency of the development process η and the time that has elapsed since project start t. It is assumed that a total number of N categories of capabilities are being utilized and that each capability (denoted by the subscript i) will be classified according to its function f_i, its nature (*i.e.* human, algorithm or hardware) n_i, its performance level p_i and its size $S_i(t)$. At time t a total of $E_{wi}(t)$ and $E_{mi}(t)$ units of the capability has been applied to the project, where E_{wi} and E_{mi} represent units of labour and materials, respectively. We now assume the following relationship between V and the other parameters (it may be of assistance to the reader to study appendix A):

$$V_p = V_p(f_i, n_i, p_i, S_i, E_{wi}, E_{mi}, \eta_i, t) \quad \text{where } i = 1, 2, \ldots, N \tag{2}$$

Replacing the first six parameters in brackets by the variable x_{ij}, and neglecting η for reasons discussed earlier, equation (2) reduces to:

$$V_p = V_p(x_{ij}, t) \quad \text{where } i = 1, 2, \ldots, N \text{ and } j = 1, 2, \ldots, 6 \tag{3}$$

Equation (3) represents value potential similar to equation (B1), and will be referred to as the planning function, as project managers intuitively apply this function when a project is being planned. The sum of the investment in knowledge resources and the running costs at any time t, which would normally be a budget constraint, is written as:

$$\begin{aligned} C &= C(f_i, n_i, p_i, S_i, E_{wi}, E_{mi}, t) \\ &= C_r(x_{ij}, t) + C_e(x_{ij}, E_{wi}, E_{mi}, t), \text{ for } i = 1, 2, \ldots, N \text{ and } j = 1, 2, 3, 4 \end{aligned} \tag{4}$$

Here C_r and C_e represent the cost of resources and the cost of effort and materials, respectively. Equation (4) will be referred to as the cost function. Additional constraints of the following form may be introduced:

$$\begin{gathered} 0 \leq p_i \leq 1, \text{ and} \\ S_i, E_{wi}, E_{mi} \geq 0. \end{gathered} \tag{5}$$

In many situations it is probable that other constraints will also apply (*e.g.* a shortage of a particular capability), but for illustrative purposes only cost constraints will be considered.

A project manager who possesses full knowledge of equation (2) would be able to optimize V_p as a function of t, subject to the constraint. Noting that f_i and n_i do not lend themselves to quantification, this optimization problem may be expressed mathematically as:

$$\frac{\partial V_p}{\partial x_{ij}} + \lambda a_{ij} = 0 \quad \text{for } i = 1, 2, \ldots, N \text{ and } j = 3, 4, 5, 6 \tag{6}$$

Here λ is a Lagrange multiplier and $a_{ij} = \partial C/\partial x_{ij}$. Equation (6) represents $4N$ distinct equations and there are a total of $4N + 1$ unknowns: x_{ij} for $i = 1, 2, \ldots, N$ and $j = 3, 4, 5, 6$ and λ. To complete the problem statement, the outstanding equation is given by equation (4).

Simultaneous solution of equations (4) and (6), at any given time, would result in the following optimum parameter set being known: V_p^*, x_{ij}^* and λ. This allows C_r^* and C_e^* to be calculated. Seeing C_r and C_e as the ordinate and the abscissa of figure 1, respectively, this optimum solution allows the construction of an optimal reference creative path. When one adds the $4N$ equations (6), the result may be written in the form $\nabla V_p = -\lambda \nabla C$. It hence follows that: surfaces of constant V_p and C touch (are tangent) at the optimum and that $\lambda = -\mathrm{d}V_p/\mathrm{d}C$.

We have reached the point where the mathematical rational for the REV nomogram can be fully developed. In order to construct the constant value lines (isovals) on the nomogram, it is attempted to minimize C_e for a given C_r and V_p. This implies that two Lagrange multipliers are needed and that equation (6) is replaced by:

$$\frac{\partial C_e}{\partial x_{ij}} + \lambda_k a_{kij} + \lambda_V a_{Vij} = 0, \text{ for } i = 1, 2, \ldots, N \text{ and } j = 3, 4, 5, 6. \tag{7}$$

Here $a_{kij} = \partial C_r/\partial x_{ij}$ and $a_{Vij} = \partial V_p/\partial x_{ij}$. For any given limits placed on the values of C_r and V_p, the solution of this new set of equations will produce the minimum obtainable value for C_e. Put differently, repeating this process for different values of C_r would produce the coordinates for the isoval corresponding to the particular V_p. Producing the REV nomogram by means of solving equation (7) has an important implication: the solution prescribes the optimum composition of resource histories (*e.g.* constitution of the design team and support as a function of time).

Reference creative paths for teams with non-optimal resources may now be constructed. By non-optimal it is implied that the created capability is, at any given time, either larger or smaller than that prescribed by the optimal creative path. These loci are obtained by minimizing C_e for a prescribed history of C_r and V_p pairs, as already described.

5. Application: technology transfer

It is anticipated that the REV technique could be used for creativity assessment in a number of fields such as engineering education, design management and technology transfer. An application in the latter field is concisely presented in the following.

Taking a chronological view of the advancement of a particular technology, it is found that a representative technological metric typically follows an ‘s-curve’ behaviour. Figure 5 is an example of a technological s-curve. The lower section of the ‘s’ represents modest growth, normally because the technology is still difficult to master and introduce. This is followed by a steep gradient, when many associated products are developed and launched on to a now receptive market. The ceiling of the curve is due to physical, economic, environmental or other limitations.

Consider the scenario where a technological leader (L) has developed a particular capability to physical maturity. In a developing country, another company (F1) is interested in acquiring

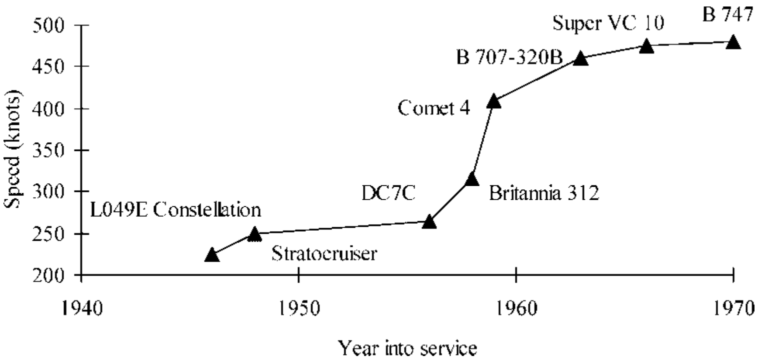

Figure 5. Growth in aircraft speed (Stamper 1973).

this technology for strategic purposes. In order to help fund its own R&D efforts, L agrees to sell a fraction of its capability to F1, and an agreement is reached. At a later stage, L has securely moved on to alternative markets and now feels safe to sell a larger chunk of the initial capability to a third company, F2. As time progresses, both F1 and F2 devote R&D effort on advancing their individually acquired capabilities. It is now shown how application of the REV technique sheds light on the efficiency of these efforts. In order to illuminate essentials, quantification of the situation is highly simplified.

Assume that the s-curve of the technological quality metric can be approximated by an equation of the form:

$$V = \sin^2 \theta \tag{8}$$

where

$$\theta = \frac{\pi}{2}\frac{t}{T} \text{ and } 0 \leq \theta \leq \frac{\pi}{2}$$

and T is the period over which the capability was developed by L. The size of the development team varied according to

$$S = S_l \sin 2\theta$$

which allows estimation of the progression of effort (in labour-time units) as follows:

$$\begin{aligned} \mathrm{d}E &= S\mathrm{d}t \\ &= E_t \sin 2\theta \mathrm{d}\theta \\ \therefore\ E(\theta) &= E_t \sin^2 \theta \end{aligned} \tag{9}$$

Here $E_t = (2/\pi)TS_l$ is the total effort required to have developed the technology. If c_e presents unit labour costs (including materials), it is clear that the total investment in the technology is $C_t = c_e E_t$. The performance level, p, is equated to V. Company L offers its capability at a price:

$$\begin{aligned} C_r &= c_r V(1 + \alpha V) \\ &= c_r p(1 + \alpha p) \end{aligned} \tag{10}$$

where the quantities c_r and α are adjusted according to company commercial interests. This equation demands a non-linearly increasing price for increasing capability. Let θ_s represent the effective entry point to the technology; that is, θ_s is that value of θ that corresponds to the bought-in technology level V (or p), according to equation (8). Further in-house R&D

converts an effort ΔE into an achieved technology level V that corresponds with the angular variable $\theta = \theta_s + \phi$. Companies F1 and F2 may consider solving the following problem: find the optimum pair θ_s and ϕ to maximize:

$$V = \sin^2(\theta_s + \phi) \tag{11}$$

subject to the total cost constraint:

$$\begin{aligned} C &= C_r + C_e, \text{ where} \\ C_r &= c_r \sin^2\theta_s(1 + \alpha\sin^2\theta_s) \end{aligned} \tag{12}$$

and, using equation (9):

$$\begin{aligned} C_e &= c_e\Delta E \\ &= C_t[\sin^2(\theta_s + \phi) - \sin^2(\theta_s)] \end{aligned} \tag{13}$$

In other words, how much should be bought-in (represented by θ_s), and how much should afterwards be spent on in-house development (represented by ϕ), such that V is an optimum for a given cost constraint C?

The simple mathematical form of the equations allows equations (6) and (4) to be solved readily, leading to the following optimum solution:

$$\begin{aligned} \lambda &= -\frac{1}{C_t} \\ \theta_s^* &= \sin^{-1}\sqrt{\frac{1}{2\alpha}\left\{\frac{C_t}{c_r} - 1\right\}} \text{ and} \\ \phi^* &= \frac{1}{2}\cos^{-1}\left[\cos 2\theta_s^* - \frac{2}{C_t}\{C - c_r\sin^2\theta_s^*(1 + \alpha\sin^2\theta_s^*)\}\right] - \theta_s^* \end{aligned}$$

An optimum solution of course only exists if the magnitude of the arguments of $\sin^{-1}$ and $\cos^{-1}$ are not greater than one, and if the square root is a real number. For this particular case, the applicable parameter values appear in table 1.

It follows that $C_t = \$86.4 \times 10^6$, $E_t = 7.2 \times 10^4$ labour-months, $\theta_s^* = 0.5932$, $p^* = 0.3125$, $\lambda = -1.157 \times 10^{-8}\,\$^{-1}$ and $\mathrm{C}_r^*/\mathrm{C}_t = 0.1563$. Progression of the optimum creative path is found by prescribing specific values for total cost C (table 2).

The REV diagram is shown in figure 6, with the optimum creative curve superimposed. The isovals were obtained by solving for (C_e, C_r) loci by prescribing V and C_r, solving for θ_s and ϕ from equations (12) and (11), respectively and then obtaining C_e from equation (13). Lines of constant cost are shown as solid lines with negative slopes. Note the tangency of the latter with the isovals at the optimum solution. In order to explain the meaning of this optimum path, money flow graphs are shown in figure 7. The 'labour' curve is the dimensionless cost required to develop the technology from scratch, given by $c_e \times E(\theta)$. The 'buy-in' curve is

Table 1. Applicable parameter values for technology leader L.

Parameter	T	S_ℓ	c_e	α	c_r
Units	Months	Labour	\$/labour-month	–	\$
Size	120	$300 \times \pi$	1200	5×10^5	276

Table 2. Optimum technology progression as a function of total investment.

C/C_t	ϕ^*	V^*	C_e^*/C_t
0.1563	0.0000	0.3125	0.0000
0.2938	0.1421	0.4500	0.1375
0.4313	0.2802	0.5875	0.2750
0.5688	0.4256	0.7250	0.4125
0.7063	0.5977	0.8625	0.5500
0.8438	0.9774	1.0000	0.6875

the dimensionless cost required to buy the technology from company L for any θ, as given by equations (8) and (10). The 'total' curve represents, for any θ, the sum of C_r/C_t and the dimensionless cost required to complete the technology development in-house, $1 - C_e/C_t$. The minimum cost of $C/C_t = 0.8438$ corresponding to $\theta_s^* = 0.5932$ is apparent from the latter graph. However, due to the low knowledge level corresponding to the optimum $(p^* = 0.3125)$, prohibitively long additional development times might preclude choosing the lowest cost option (observe the long optimum creative path, from entry up to $V = 1$; figure 6). Put differently, for the technology followers F1 and F2, it might be wiser to purchase the technology at the highest level on offer, in order to minimize further development risks and lengthy times to market of their own products. A more comprehensive analysis would consider an additional constraint on time to market.

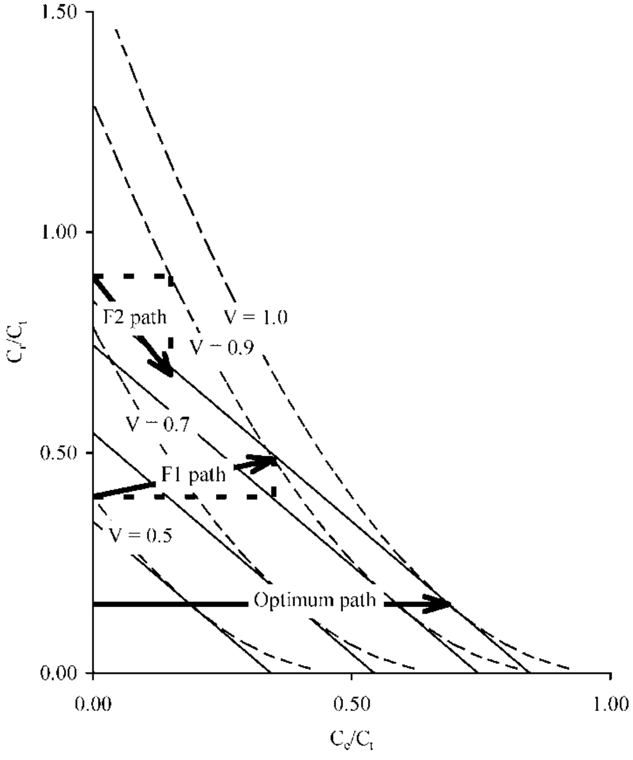

Figure 6. REV diagram for technology transfer example.

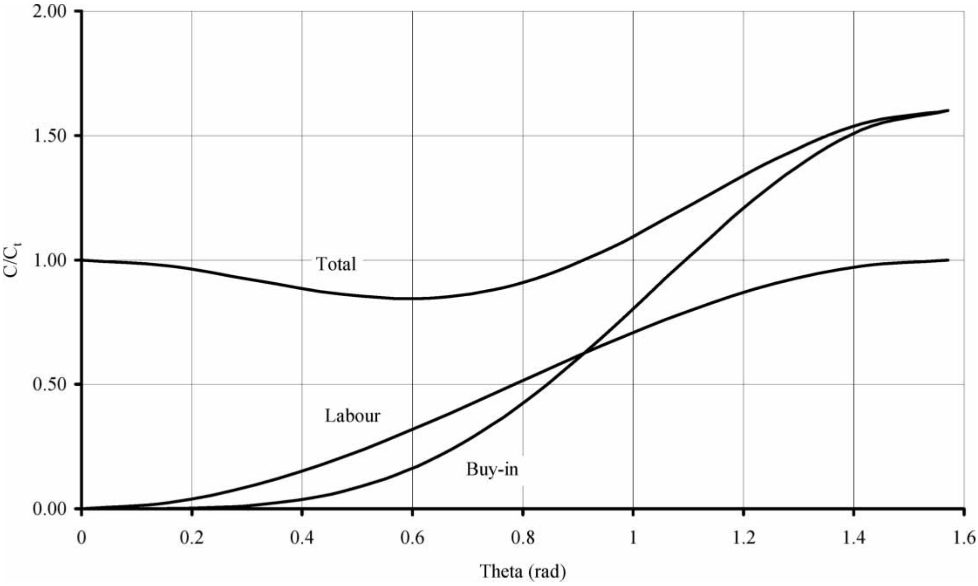

Figure 7. Cash flow histories.

Table 3 presents some major parameters with regard to the development histories of F1 and F2. The first column shows the bought-in capability. The second column contains the corresponding dimensionless investment. The third column gives the dimensionless cost expended on further development at the time when major technology reviews were independently conducted at the two companies. The achieved capability appears in the final column.

The question is, which one of the two companies is technologically more creative? From the table it is not apparent. Although F1 has the higher achieved V_a, this company has devoted much more R&D effort to technology advancement then did F2. Using the REV approach to resolve this matter, the two respective data points, for the start and review stage, are plotted for both companies in figure 6. The comparative slopes of the resulting creative paths immediately suggest that F1 is more creative than F2. Equation (B3) may be used to calculate creativity, either by:

- interpolating for the values of V_p on figure 6 (the intersecting points of the thick dashed lines); or
- solving for the V_p values algebraically by using the appropriate equations from those given above, and then calculating the creativity from $\eta = V_a/V_p$.

Table 4 contains the results.

Table 3. Development histories of technology followers F1 and F2.

	V_s	C_r/C_t	C_e/C_t	V_a
F1	0.5	0.4	0.35	0.9
F2	0.75	0.9	0.15	0.8

Table 4. Calculated technological creativity of companies F1 and F2.

	V_a	V_p	η
F1	0.90	0.85	1.06
F2	0.80	0.90	0.89

Company F1's creativity not only exceeds that of F2, but F1 turns out to be even more creative than the technology leader, company L. By studying figure 6, it should be clear that the graphical portrayal of inventive histories as summarized on the REV diagram vividly consolidates and monitors the efficiency of R&D efforts.

6. Conclusion

A method for the assessment of the creativity of new product designers was introduced. Technological creativity is seen as a relative efficiency of design value generation. The method relies mainly on three assumptions: a creative contribution in engineering design is detectable through either measurable improvements of product value parameters, a reduction in required development effort or resources, or a combination of these effects; the value of a design in progress may be expressed as a function of various product parameters, all normally only partially validated and verified (equation (1)); and the potential value of a design conducted by a reference designer may be expressed as a function of the available resources and effort applied (equation (2)). The former and latter functional forms may be viewed as *achieved value* and *potential value*, respectively. The potential value function allows the construction of both the REV nomogram and a reference creative path; the achieved value function allows the construction of an achieved creative path on the nomogram and the calculation of creativity. A case study is discussed that shows how a REV nomogram may be generated by processing project planning data. An application of the methodology in the field of technology transfer is given, illustrating how the REV diagram vividly portrays the creative performance of R&D teams.

It is emphasized that the present definition of creativity allows the detection of creative contributions resulting either from product invention, from design process improvement or from efficient application of resources, or from combinations of the three factors. For example, at a particular point in the design process, achieving a particular product quality with less effort than would be required by the reference designer would result in $R_r > R$ (figure 2); hence the candidate's creativity would exceed the value one (equation (B3)). In this case, the candidate designer added value to the design process. As an example of efficient application of resources, consider the creative performance of a large, highly educated design team with access to ample and sophisticated development facilities. Their vast resources would result in the construction of a high reference creative path in figure 2, relative to the reference creative path constructed for a much smaller team. Assuming that, due to inefficiencies in the larger team, both teams achieve the same design value measurement after equal effort, it should be obvious that equation (B3) would give a lower creativity value for the larger design team.

Based on the ideas as presented in this paper, a number of projects is being planned in order to develop the REV methodology as a programme management tool and as a creativity assessment aid in engineering education.

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Appendix A: demonstration of the existence of the REV nomogram

It will now be demonstrated how the REV nomogram may be generated by appropriately manipulating standard programme management tools such as Gantt diagrams and resource schedules. A heuristic approach that will hopefully elucidate the mathematical model of the paper will be followed. A simple case study, a garden landscaping project, is deliberately chosen for illustrative purposes.

Consider the planning data for a particular project, as generated by a garden landscaper (figure A1). This figure shows the various activities to be performed and the associated time-line bar chart. The required activities are: management, lay-out design, preparation of the site to be landscaped, refuse removal, supply of equipment and plants, and planting. Three major phases are also shown on the figure. As far as four of the activities are considered, the landscaper has the option to have them executed either by himself/herself or by a subcontractor. These activities have two options each and hence there are $2^4 = 16$ possible ways to conduct the project. The costs associated for both internal and external activity execution are indicated in figure A1. Table A1 summarizes the 16 options and the costs of internal effort and external assistance, respectively, for the three phases.

For all 16 possibilities, (C_e, C_r) value pairs from table A1 are plotted as triangular nodes (milestones) on figure A2. The thin solid lines connecting nodes indicate the completion of the various phases, and each implies particular value added to the effort. Note the jagged appearance of two of the value lines. Each of the 16 contractual options is identified by means of a number and chain lines connecting its nodes. Constant total project costs appear as broken straight lines with negative slope on the figure. ‘Frontiers’ are now constructed for each phase by starting at the uppermost node and drawing a straight line to another node below it, where the latter node is carefully selected such that extension of the straight line would result in all other nodes falling to its right. For phases two and three, the frontiers are shown as thick solid lines.

Figure A2 can be converted into a REV nomogram by introducing the following two idealizations:

(a) Activity Sharing, implying an activity may be split into two subactivities, permitting one to be conducted externally and the other internally, without sacrificing product value or time.

	Cost/garden		Schedule		
	External	Internal	Phase 1	Phase 2	Phase 3
	$	$			
Manage		200		■	■
Lay-out design	400	200	■		
Prepare site	200	400		■	
Remove refuse	200	100		■	
Supply equipment and plants	300	400		■	■
Plant		500			■

Figure A1. Planning data for gardening project.

Table A1. Costs associated with various activity allocation options.

					Period C_e($)			Period C_r($)		
Option	Design	Prepare	Remove	Supply	1	2	3	1	2	3
1	Int	Int	Int	Int	200	1000	1800	0	0	0
2	Ext	Int	Int	Int	0	800	1600	400	400	400
3	Int	Ext	Int	Int	200	600	1400	0	200	200
4	Ext	Ext	Int	Int	0	400	1200	400	600	600
5	Int	Int	Ext	Int	200	900	1700	0	200	200
6	Ext	Int	Ext	Int	0	700	1500	400	600	600
7	Int	Ext	Ext	Int	200	500	1300	0	400	400
8	Ext	Ext	Ext	Int	0	300	1100	400	800	800
9	Int	Int	Int	Ext	200	800	1400	0	150	300
10	Ext	Int	Int	Ext	0	600	1200	400	550	700
11	Int	Ext	Int	Ext	200	400	1000	0	350	500
12	Ext	Ext	Int	Ext	0	200	800	400	750	900
13	Int	Int	Ext	Ext	200	700	1300	0	350	500
14	Ext	Int	Ext	Ext	0	500	1100	400	750	900
15	Int	Ext	Ext	Ext	200	300	900	0	550	700
16	Ext	Ext	Ext	Ext	0	100	700	400	950	1100

(b) Activity Gain, implying that if a certain fraction of an activity has been completed, a pro-rata fraction of the value associated with the activity will have been gained.

These idealizations imply that a project manager may select any coordinate on a frontier as a target, and devise an activity schedule that will ensure achievement of this goal. For example,

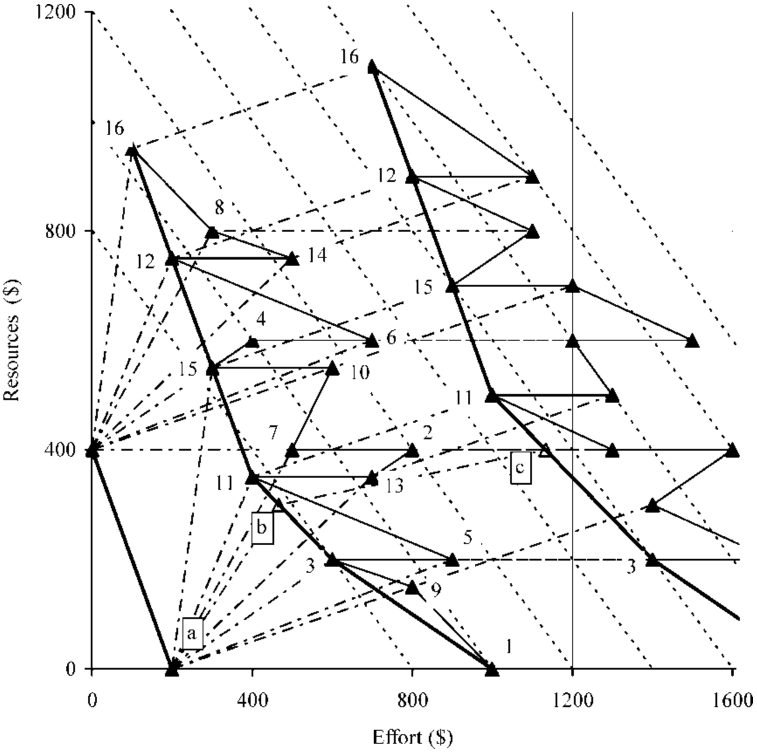

Figure A2. Generation of the REV nomogram.

points b and c may be selected as realizable targets (figure A2), where these points lie one-third of the line segment lengths 11:3 below nodes 11. The rule that allows this to be achieved is presented here without proof:

> Let k and $k+1$ be nodes on a particular frontier. Assuming the validity of Activity Sharing and Activity Gain, the project can be managed such that the value associated with the frontier can be achieved for any chosen point on the line segment $k+1:k$. If the chosen point lies a fraction f of the line segment length from node $k+1$, say, the procedure is as follows: Identify the activities that are differently allocated in the preceding phase for options k and $k+1$. Split each of these activities into two sub-activities of fractional sizes f and $1-f$. Considering all the sub-activities of fractional size $1-f$, each one of these is allocated internally (externally) if option $k+1$ requires it to be allocated internally (externally). Each one of the remaining sub-activities of fractional size f is allocated internally (externally) if option $k+1$ requires it to be allocated externally (internally).

Application of this rule is now demonstrated for points b and c of figure A2. Applying the above rule to b first, note which activities are allocated differently in phase 2 for nodes 11 and 3 (table A1). There is only one, supply of equipment and plants, which is allocated externally and internally for nodes 11 and 3, respectively. In this case $f = 1/3$ and $1 - f = 2/3$ following the rule, two-thirds of 'supply' should be allocated externally, and one-third internally. The coordinates for b are now calculated as follows:

$$C_e = 200 + 200/2 + 100 + 1/3(400/2) = \$466.7 \text{ and } C_r = 200 + 2/3(300/2) = \$300$$

Similar reasoning for c leads to its coordinates, as follows:

$$C_e = 466.7 + 200/2 + 500 + 1/3(400/2) = \$1133.4 \text{ and } C_r = 300 + 2/3(300/2) = \$400$$

The correctness of these values is easily checked by means of linear interpolation between nodes 11 and 3.

The frontiers on the diagram are hence loci of realizable project goals and represent optimum creative process performance for given required added value and specified contracting schedules. The frontiers correspond to isovals of the REV nomogram and replace the original jagged lines. The idealization of Activity Gain allows any point on the diagram, not necessarily falling on an isoval, to be associated with a particular added value. This is done by specifying the added value and interpolating between corresponding nodes on isovals.

Discarding the original jagged and dashed lines, figure A2 can be summarized as a multidimensional graph, linking three variables: cost of resources, cost of effort and added value. This functional dependence applies to a large area of the graph, called the domain. The independent variable (added value) exists, is continuous and differentiable over the entire domain (the earlier discussion can be easily modified to allow replacement of the segmented straight line isovals with smooth contours and interpolating by means of splines). The added value corresponding to specific coordinates on the graph is achievable in an ideal creative environment, wherein the creator is efficient and the idealizations presented apply. A specific 'creative path', or locus of (C_e, C_r) coordinates, applies to each coordinate in the domain (assuming that paths connecting similar nodes do not cross). Data for imperfect creators can be plotted on the graph for creativity assessments as discussed in the main body of the paper, using the diagram as a REV nomogram.

A summary of capabilities, effort and resources for management approach a–b–c (figure A2) is presented in table A2, highlighting the structure of the planning function, equation (2).

Appendix B: creativity as efficiency of design value generation

Defining creativity in engineering design as the relative efficiency of design value generation, an equation for the calculation of creativity is derived as follows. The almost hyperbolic shapes

Table A2. Capabilities, effort and resources for creative path a-b-c.

			Effort and resource history					
			Phase 1, achieved value $= 1/2$		Phase 2, achieved value $= 1/2$		Phase 3, achieved value $= 1$	
Capability #	Function	Nature	Labour + mat	Resources	Labour + mat	Resources	Labour + mat	Resources
i	f_i	n_i	C_e	C_r	C_e	C_r	C_e	C_r
1	Manage	Human			100			
2	Design	Human & HW & SW	200					
3	Prepare site	Human & HW				200		
4	Remove refuse	Human & HW			100			
5	Supply	Human & HW			66.7	100	66.7	100
6	Plant	Human & HW					500	
		Cost per phase ($)	200	0	266.7	300	566.7	100
		Cumulative cost ($)	200	0	466.7	300	1033.4	400

of the *isovals* (lines of constant value) of figure 1 suggest that the potential to conceive a design of a particular value should depend on the product of available resources R and devoted effort E. Hence, the following definition for value potential V_p is put forward (see comment at the end of this appendix):

$$V_p = \frac{RE}{g(R, E)} \tag{B1}$$

Here the empirically determined function $g(R, E)$ allows the isovals to deviate from a hyperbolic shape, and for return to scale effects. It is clear that V_p also represents the input to the design process, with regard to resources and effort.

Remembering that figure 1 is to be constructed based on the creative capabilities of the reference designer, it is probable that the candidate designer will achieve a design value V_a that will in general be smaller than V_p. But to achieve a value of V_a after E units of effort, the reference designer would only have needed R_r units of knowledge resources (figure 2). Hence:

$$V_a = \frac{R_r E}{g(R_r, E)} \tag{B2}$$

Equation (B2) represents the output of the design process (at this particular stage). Defining creativity thus as an efficiency η, or as output divided by input, the following quantified definition is obtained from equations (B1) and (B2):

$$\begin{aligned} \eta &= \frac{V_a}{V_p} \\ &= \frac{R_r}{R}\frac{g(R, E)}{g(R_r, E)} \end{aligned} \tag{B3}$$

Comment: The Cobb–Douglas production function (Gujarati 1995) has the form $Q = \alpha K^{\beta} L^{\gamma}$, where Q is output, K is physical capital and L is labour. The sum $\beta + \gamma$ gives information about returns to scale, (*i.e.* the response to output Q to a *proportionate* change in the inputs K and L). If this sum equals one, we have constant returns to scale. If the sum is less or greater than one, we have decreasing or increasing returns to scale, respectively. However, technological s-curves represent *variable* returns to scale (first increasing and then decreasing), implying that the Cobb–Douglas function is not ideal for creativity assessment, and the form of equation (B1) is preferred.