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On the Economics and Analysis of Diversity

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Abstract

A review of the literature reveals that the concept of diversity (and especially technological diversity) is of considerable general significance in economics. Diversity is variously argued to be a major factor in the fostering of innovation and growth, an important strategy for hedging against intractable uncertainty and ignorance, the principal means to mitigate the effects of ‘lock-in’ under increasing returns and a potentially effective response to some fundamental problems of social choice. Recognition of the countervailing costs and wider disadvantages associated with diversification simply compounds the case for the development of a clear, comprehensive and systematic general operational characterisation of diversity in economics.

Perhaps surprisingly, then, it is found that existing approaches to the analysis of technological and wider economic diversity tend either to be rather rudimentary or quite circumscribed in character. Drawing on analytical approaches to the concept of diversity undertaken in a range of disciplines (including economics, ecology, palaeontology, archaeology, psychology and chemistry), this article sets out a formal threefold general characterisation of diversity. A variety of quantitative indices are examined and a novel integrated index of ‘multi-criteria diversity’ is developed and evaluated under this framework. The potential utility of this index is assessed in a more practical (but still hypothetical) exercise which seeks to illustrate how trade-offs might systematically be explored between diversity and wider economic performance in real portfolios of technologies, such as those employed in the electricity supply industry.

Acknowledgements

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INTRODUCTION

The present working paper is in three main parts. ***Part 1*** reviews four areas of the economic literature where there exists a strong interest in diversity. *Section 1.1* explores the notion of economic diversity as a means to promote beneficial forms of innovation and growth. *Section 1.2* develops the idea that diversification may offer a basis for a decision making heuristic under strict uncertainty and ignorance, which may be more robust than the use of probabilistic approaches under these conditions. Reviewing the historical and sociological (as well as the economic) literature on ‘sociotechnical systems’, *Section 1.3* identifies diversity as a strategy for mitigating the adverse effects of institutional ‘momentum’ and ‘lock-in’ in long term technological trajectories. *Section 1.4* argues that economic diversity presents a way of responding to the notorious ‘Arrow Impossibility’, by accommodating the disparate array of interests and values typically associated with social choice in modern pluralistic industrial societies.

Having established a basis for an interest in the analysis of economic diversity (and the associated trade-offs between diversity, cost and other aspects of economic and wider social performance), ***Part 2*** discusses a range of different disciplinary approaches to the general characterisation of diversity. Drawing principally on economics and the biological sciences, *Section 2.1* reviews some conventional perspectives and proposes a formal threefold qualitative definition of diversity. On the basis of this scheme, *Sections 2.2* and *2.3* discuss various quantitative indices that are applied in different fields to the measurement of different aspects of diversity.

Part 3 addresses one way in which economic diversity might be analysed and the trade-offs with other aspects of performance systematically explored. *Section 3.1* places the analysis of economic diversity in the context of the routine appraisal of portfolios of investments, technologies and policies. *Section 3.2* proposes a novel index of diversity and demonstrates some of its most important properties. *Sections 3.3* and *3.4* show in some detail how such an index might be applied in the practical task of appraising economic options, taking account of trade-offs between different performance criteria and portfolio interactions. Finally, in *Section 3.5*, the potential practical applications of the resulting ‘diversity optimisation’ procedure are demonstrated in a hypothetical exercise study focussing on a case study concerning technology choice in the UK electricity supply sector.

1. DIVERSITY IN THE ECONOMY

1.1 Fostering Innovation

The concept of diversity has long been central to economics. Diversity is the basis for consumer choice [1]. It is a prerequisite for competition [2]. The role of diversity in labour and factor endowments, though often implicit, is fundamental to economic theory [3]. Indeed, Ricardo's insight concerning 'comparative advantage', which is essentially founded on the consequences of diversity, has been identified as the one proposition in the whole of social science which is at the same time true and non-trivial [4]. Yet neoclassical orthodoxy tends to treat important economic entities such as households, firms and technologies as if they were essentially homogenous [5]. Although some, like Schumpeter, realised early on that diversity in consumer goods is "one of the fundamental impulses that set and keep the capitalist engine in motion" [6], relatively little attention has traditionally been devoted to the systematic exploration of the nature and implications of diversity in economics [7].

With the advent of 'institutional' and 'evolutionary' approaches [8], newly intensified interest in the dynamics of real economies over time and a realisation of the importance in the economy of qualitative structural change [9], the concept of economic diversity has recently come to the fore [10]. Drawing on a momentous (but somewhat tautologous) metaphor from the biological sciences [11], diversity is seen to drive economic evolution, whilst it is evolution which is held to create diversity [12]. Yet, recognition of the fundamental importance of economic diversity is not confined to evolutionary-theoretic approaches. Repeated calls are made for the detailed empirical and theoretical examination of diversity in areas such as consumer characteristics, products, production processes and organisational forms [13]; research strategies [14], competences

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[1] Geroski, 1989.

[2] Gatsios and Seabright, 1989.

[3] Cohendet, Llerena and Sorge, 1992; Llerena and Llerena, 1993:224.

[4] The economist P. Samuelson quoted by Brockway (1993:299). Similar notions founded on concepts of diversity in ecological agents are important in evolutionary biology (Ridley, 1996).

[5] Llerena and Llerena, 1993:224.

[6] Schumpeter, 1912:83. The term used by Schumpeter was actually 'variety' - the distinction between this and 'diversity' is discussed later in this article (Section 2.1) but is not pertinent here.

[7] Cohendet, Llerena and Sorge (1992) describe the amount of attention as "insignificant".

[8] Although built on old roots (eg: Veblen, 1898; Schumpeter, 1912, 1942), it is only in recent years that evolutionary perspectives have begun to gain ground in economics, as exemplified by the proliferation of books on this general theme, eg: Nelson and Winter, 1982; Freeman, 1982; Axelrod, 1984; Clark and Juma, 1987; Dosi et al, 1988; Anderson, Arrow and Pines, 1988; Clark, 1985; Dosi, Pavitt and Soete, 1990; Loasby, 1991; Saviotti and Metcalfe, 1991; OECD, 1992; Hodgson, 1993; Foray and Freeman, 1993; Faber and Proops, 1994; Vromen, 1995; Saviotti, 1996; Landau, Taylor and Wright, 1996.

[9] Saviotti, 1991.

[10] Bruno, Cohendet and Desmartin, 1991:10.

[11] As exemplified in an analogy with fire reportedly expressed enigmatically by Lewontin (1982:151) to the effect that "selection is like a fire that consumes its own fuel … unless variation is renewed periodically evolution would have come to a stop almost at its inception" (cited in David and Rothwell, 1996:186). That this analogy might work better if selection were held to 'produce' rather than 'consume' "…its own fuel", is just one instance of the ambiguities of biological evolutionary metaphors.

[12] Cf: Llerena and Llerena, 1993; Cohendet, Llerena and Sorge, 1992.

[13] Eg: Bruno, Cohendet and Desmartin, 1991.

[14] Landau, Taylor and Wright, 1996; Rosenberg, 1996.

and learning processes [15]; technologies and modes of innovation [16]; investor expectations [17] and customer choice and competition [18]. For better or worse, the diversity cat at last seems safely out of the neoclassical bag.

The newly emerging interest in diversity is perhaps most pronounced in the economics of technology. After years in which economists generally seemed content to consign this subject to the status of a 'black box' [19], it is now a well-rehearsed assertion that studies in this area have undergone an important transformation [20]. There is a move away from a simplistic 'linear' understanding of the relationships between science, technology and the economy, and towards a more 'interactive' model of the aetiology of technological innovation [21]. In the process, interlinked concepts of technological and institutional diversity are coming to occupy something of a central place. Reflecting long-established insights from finance management, economic diversity in all its forms is increasingly argued to offer a "resource pool". Whether in the development of technologies, the marketing of products, the recruitment of customers or the securing of suppliers, the deliberate pursuit of portfolios of options is seen to confer 'resilience' in the face of uncertainty and ignorance [22].

This well-worn theme is explored in some detail from a different angle in the next section. First, however, it may be useful to review a more recent and less well-recognised dimension to the economics of diversity which has implications far beyond the confines of the economics of technology. For there is now developing a substantial literature in which technological and institutional diversity is credited rather direct causal properties in the fostering of general economic innovation and growth. For instance, empirical observations have been made in some areas to the effect that the 'rate of progress' displayed within a particular industry tends to be proportional to the "degree of economic variety contained within it" [23]. Likewise, it is reported in a number of studies that "growth of cities appears most strongly correlated with industrial diversity and not with concentration within single industries" [24]. Indeed, the evidence for the central importance of diversity for the economy as a whole seems so compelling to some economists, that they are moved to conclude that "a trend towards growing variety is … one of the fundamental trends in economic development" [25] with growth in technological diversity in particular held to be "a necessary requirement for the continuation of long term economic development" itself " [26]. Irrespective of the many crucial analytical questions and evaluative issues surrounding the form

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[15] Eg: ; Dosi, 1990; Cohendet, Llerena and Sorge, 1992.

[16] Eg: Bruno, Cohendet and Desmartin, 1991; Cohendet and Llerena, 1995.

[17] Eg: Dosi, Orsenigo and Silverberg, 1986.

[18] Eg: Gatsios and Seabright, 1989.

[19] This famous phrase is Rosenberg's (1982). Of course, there are always exceptions (David, 1975).

[20] See, for instance, much of the recent material cited in footnote **8** above.

[21] OECD, 1992.

[22] The term is that of Llerena and Llerena, 1993. Grabher and Stark (1997) also refer to institutional diversity in terms of an economic "resource for the future".

[23] Gibbons and Metcalfe, 1986.

[24] Kauffman, 1993.

[25] Saviotti, 1996:93. This issue is discussed in more detail in Section 2.3.1.

[26] Saviotti and Mani, 1995.

and direction of economic ‘progress’, ‘growth’ and ‘development’, it seems clear that the concept of diversity is coming to occupy a prominent position in the work of many contemporary economists [27].

Before looking at the other side of this picture - including some of the difficulties and trade-offs associated with diversification – it may be useful to review some different ways of thinking about the role and mechanics of diversity in relation to the fostering of innovation and growth. Many of the more innovative perspectives come from various forms of network theory. One such approach derives from the burgeoning field of so-called ‘complexity science’. In Kauffman’s ‘grammar models’, for instance, the dynamics and complementarities displayed by different goods and services in the economy are represented in stylised form as information ‘strings’. Innovation and ‘technological coevolution’ are modelled (without reference to costs, prices or values) simply as the interactions that operate between strings with the result of generating new strings. In this context, economic diversity is characterised simply as the number of different strings in circulation at any one time [28]. In repeated runs of such models, Kauffman observes that the coupling of separate systems tends consistently to lead to explosive ‘take off’ , confirming for him that “technological diversity is a major factor in abetting economic growth” [29].

Under a qualitative (but more empirically sophisticated), sociological approach, Callon and his associates have over the years repeatedly documented the critical role of ‘actor’ and ‘techno-economic networks’ in the development and dissemination of technological (and associated institutional) innovation [30]. Again, an important means to promote innovation is held to reside in the fostering of linkages between ‘*heterogeneous*’ technological and institutional actors [31]. According to this conceptually rich (but sometimes rather abstract) body of work, the entire undifferentiated edifice of science and technology [32] is best thought of as “a product of interaction between a large number of *diverse* actors” [33]. In seeking to understand the dynamics of innovation and dissemination, Callon focuses on the effectiveness of the conceptual ‘translations’ between actors (such as research and marketing managers, financiers, regulators, customers, suppliers, academics and educators) as well as inanimate ‘actants’ (such as the physical materials and engineered systems

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[27] The present author’s own use here of the terms ‘growth’, ‘progress’ and ‘development’ for the moment simply reflects the economic usage which it is the purpose of this section to describe. The often rather loose and unqualified use of these concepts in economics raises serious analytical as well as evaluative questions, some of which will be returned to later in this paper (Section 3.1). For present purposes, however, it should be noted that the question of links between technological and institutional diversity and more general social and economic ‘progress’, ‘growth’ and ‘development’ is important even where these concepts are formulated in broader, more pluralistic, finely diifferentiated and less materialistic terms than is the norm in economics (eg: Redclift, 1987; WCED, 1987; Daly, 1987; Daly and Cobb, 1989; Daly and Townsend, 1993; Norgaard, 1989, 1994; Jacobs 1990, 1996; O’Neill, 1993; Killick, 1995; Becker and Ostrom, 1995; Bartlett, 1996). After all, even the most ‘progressive’ of paths toward the most ‘steady state’ of ‘sustainable’ futures will require growth in certain institutions, sectors and technologies. The more radical the rate of change envisaged toward ‘sustainability’, the greater the degree of ‘progress’, ‘growth’ and ‘development’ required of the technologies and institutions concerned - with corresponding implications for diversity.

[28] Kauffman, 1993.

[29] It is interesting that in these models diversity tends to an asymptote with increasing length of planning horizon (Kauffman, 1993). Also of potential relevance here is Kirman’s observation that the tendency in stochastic models of an n-dimensional simplex to reside at extremes underscores the importance of retaining options at low system penetrations (Kirman, 1992).

[30] Callon, 1986a, 1990, 1992, 1996; Callon, Law and Rip, 1986; Callon et al, 1992.

[31] De Laat, Callon and Laredo, 1997.

[32] Or ‘technoscience’ (Callon, Law and Rip, 1986).

[33] My emphasis. Callon, 1991:132.

themselves) [34]. Under this view, the ‘durability’ and ‘robustness’ of the resulting innovations arise, in part, from the ‘irreversibility’ of the associated sustaining networks. This, in turn, depends partly on the ‘heterogeneity’ of the actors embedded in the networks, thus illuminating some of the social mechanisms by which economic diversity may be seen to have a direct effect on the conditions sustaining particular innovations [35] - and so to consequent economic ‘success’.

Indeed, the scope for generating beneficial innovations through diversity may extend beyond technology in the narrow sense. The greater creative intensity of more pluralistic societies seems to be something of a received wisdom in cultural studies [36]. Social diversity and pluralism are widely held to foster institutional as well as technological innovation [37]. In particular, these insights underscore with respect to technology a phenomenon noted in some detail by Kuhn in relation to scientific knowledge [38]. Here, some of the most creative innovations are seen to arise through the cross-fertilisation of disparate disciplines or traditions. All else being equal, then, a culture in which diverse institutional, technological and epistemological systems are maintained in parallel might be expected to provide an environment which is more conducive to intensive, radical and (in at least some sense) genuinely ‘beneficial’ innovations.

These sociological insights concerning the formative importance of diversity may quite readily be framed in terms of the more mainstream economics and history of technology [39]. For instance, the perception of an eclectic, assimilative and pluralistic quality in late Mediaeval European society is often seen as a seminal influence on the ensuing epoch of rapid technological change and economic growth [40]. Likewise, socio-economic and cultural diversification may also be seen to play a role in Landes’ recognition of the crucial importance of increased social mobility in the early British Industrial Revolution [41]. The benefits of diversity in providing for more effective ‘search strategies’ under uncertainty are much discussed and are reviewed in the next section [42]. Calls for the fostering of greater diversity in public support for scientific research and development, however, go beyond this, being predicated not just on uncertainty, but on the benefits accruing from the cross-fertilisation of disparate skills [43]. Recommendations that “[g]overnment policy ought to be to open many windows and to provide the private sector with financial incentives to explore the technological landscape that can be faintly discerned through those windows” [44] also reflect an appreciation of the importance of diversity in learning

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[34] In addition to references above, see also: Callon, 1986b; Callon, 1986c.

[35] Callon, 1991, especially: pp.89-92. See also Callon, 1992.

[36] Habermas, 1968; Rescher, 1993; Bohmann, 1996.

[37] Cf: Norgaard, 1989; James and Thompson, 1989; O’Neill, 1993; Mokyr, 1994; Booth, 1995.

[38] Kuhn, 1970.

[39] Although institutional and wider economic diversity play an important role in many areas of the economic history of technological innovation, the concept of diversity itself has, until recently, remained somewhat implicit and subordinate to other themes, such as Weber’s Protestantism (1930), White’s Christianity (1962) or Habbakkuk’s labour-saving imperative (1962).

[40] Cf: Hall (1957) quoted approvingly in Rosenberg 1982. It may also be recognised in Needham’s contrast between post-Mediaeval European and Chinese societies (1969b).

[41] Landes, 1969.

[42] Section 1.2.

[43] For instance, Pavitt (1989) states that “...too much attention … [is] devoted to [a] relatively narrow range of scientific fields producing knowledge with direct technological applications and too little to the much broader range of fields, the skills of which contribute to most technologies”.

[44] Landau, Taylor and Wright, 1996:17.

strategies [45].

Here, economists of technology have identified a further useful conceptual pointer to the potentially important role of diversity – one that converges with the sociological work on ‘actor networks’. Under both perspectives a diverse array of functional and institutional imperatives may often be seen to present a more creative and demanding ‘selection environment’ [46]. Where this is so, then it may also be the case that institutional diversity acts not only to promote ‘successful’ innovations, but might also foster ‘better’ innovations (whatever this may mean [47]!). Put simply, the bottom line is that many economists are coming to suspect (in the words of Aoki) that “[o]rganisational diversity could be a source of higher global welfare” [48].

An interesting elaboration and qualification of these general insights arises from one further application of network metaphors to the economics of diversity. By reference to experience in Northern Italy and Eastern Europe for instance Grabher and Stark‘s work on the regional determinants of ‘successful entrepreneurship’ confirms that diversity is a potentially important factor in promoting adaptability in an economy. However, they also observe that too ‘noisy’ a diversity can actually risk suppressing vital selection processes [49]. Networks that are too dense or too extensive may deliver greater ‘coherence’, but they are also observed to *decrease* the adaptability of an economic system. They describe the optimal configuration of economic networks as being “loosely coupled” [50]. The associated institutional and technological “compartmentalisation” which they observe in their more successful cases, may offer a fruitful alternative perspective on the economic benefits of diversity [51].

Box 1 provides a schematic illustration of a general synthetic model of the role of diversity in economic innovation that draws on these insights from the various forms of network theory. Here, the implications of economic diversity for beneficial innovation might be seen in terms of the ‘connectivity’ in technological, institutional and functional networks. A condition of optimal diversity falls somewhere between two extremes in the degree of connectedness of an economic system: dense homogeneity on the one hand and complete fragmentation on the other. Rather than aiming at maintaining highly disparate rationalities and practices in unconnected ‘ghettos’, then, the hypothesis is, that a policy of diversification that is aimed at fostering beneficial technological and institutional innovation might better be directed at sustaining a

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[45] Here Landau et al (1996) are echoing Rosenberg’s (1996) own call for diversity (reviewed in the next section) but choose themselves to emphasise the ‘openness’ of research ‘windows’, rather than diversity.

[46] Nelson and Winter, 1977:61.

[47] The question of how to approach the notion of what is ‘beneficial’ or not is addressed later in this paper. For the moment, the adjective is used simply to qualify the common practice in the economics of technology simply (and implicitly) to assume that all innovation must necessarily be ‘beneficial’.

[48] Aoki,1996:263.

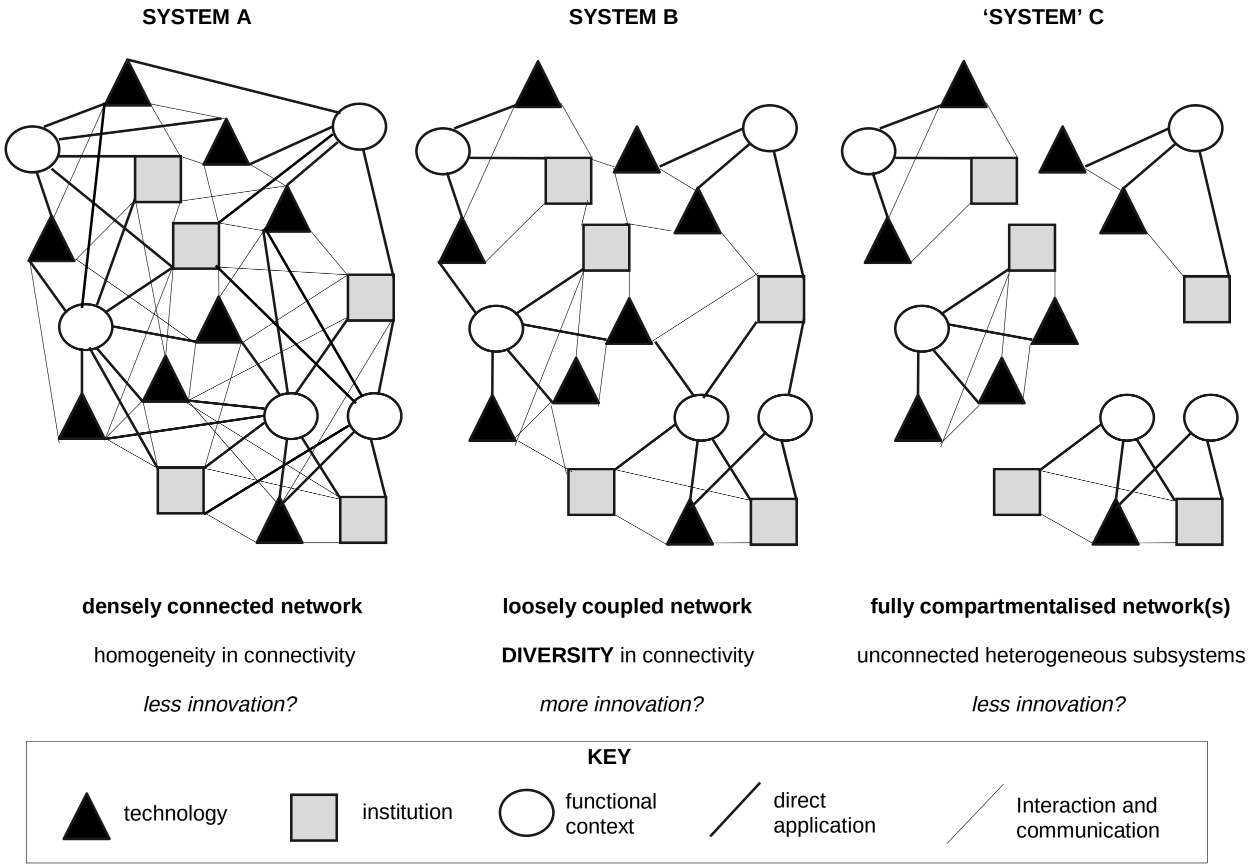
[49] Grabher and Stark, 1997.

[50] Perhaps an intriguing reflection of Kauffman’s ideas concerning the optimisation of conditions at an intermediate point between ‘ordered’ and ‘chaotic’ states (Kauffman, 1993).

[51] Grabher and Stark, 1997.

number of loosely coupled but heterogeneous pockets of local coherence. In other words, under a variety of current economic and sociological perspectives, the benefits of diversity arise through the striking of a balance between compartmentalisation and connectedness in technological and institutional networks.

Box 1: A schematic synthesis of some current ideas on networks, diversity and innovation



Some of the issues raised here are returned to in subsequent sections of this paper [52]. For the moment, it should be noted that (for all the interest that it currently seems to enjoy) the notion that economic diversity acts to foster innovation and growth can only ever be part of the story. Whatever the veracity or heuristic merits of this hypothesis may be, there is another side to the ledger. For, no matter how it is achieved, diversity cannot be assumed to be a free good. Increasing the diversity of economic activity may be expected to incur increased production costs (through foregone economies of scale) and transaction costs (through greater information requirements) [53]. In the particular case of technology, the converse of diversity (standardisation) is seen to bring important scale and transaction benefits, in addition to certain other positive

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[52] Concerning phenomena such as strict uncertainty and 'ignorance' in long term technology choice (Section 1.2), 'lock-in' and 'momentum' in sociotechnical systems (Section 1.3) and plural rationalities (Section 1.4).

[53] Cohendet, Llerena and Sorge, 1992.

learning and network externalities and flexibility gains [54]. As Weitzman portentously remarks in another context "… the laws of economics apply also to diversity. We cannot preserve everything. There are no free lunches for diversity" [55].

Accordingly, rather than advocating the wholesale 'maximising of diversity' (whatever this might mean [56]), the message from the emerging economic and sociological literature is rather that there must be a trade-off. Some balance must be struck between viewing diversity exclusively as an obstacle to scale and other efficiencies, and an unqualified rosy view of diversity as a 'resource pool' [57]. Indeed, this trade-off must take place even within certain categories of cost accounting [58]. Here, diversity can appear on both sides of the equation. For instance, though some economies of scale may be foregone in diversification, diversity may also allow the realising of certain economies of system or of scope. Likewise, although standardisation aids some forms of learning, diversity promotes others [59]. Indeed, Dosi observes that regional and institutional differentiation (rather than standardisation) may often be a sign of effective technological learning [60]. However it is conceived, there can be little doubt that the growing sophistication of information and communication technologies, and their increasing institutional integration, acts progressively to move the locus of this hypothetical 'optimal' trade-off away from standardisation and towards diversity [61].

Left at this, however, discussion of the merits and shortcomings of economic diversity remains highly unsatisfactory [62]. The crucial questions that form the basis for this paper remain effectively unanswered. What exactly is diversity? Which things might best be diversified? How might we go about resolving the best trade-offs in different situations? What are the implications for practical policy making and investment decisions? The history of corporate strategies and industrial policies is replete with examples of what in retrospect appears to have been the misplaced pursuit of diversity [63]. The point is not simply to document its (rather obvious) existence, but to be more systematic in accounting for the implications. For technologies or institutions that are marginalised or in decline - perhaps for very good reasons - appeals to the general virtues of diversity may offer an alluring strategy for advocacy [64]. Here, the benign "apple pie" connotations of diversity

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[54] Cowan, 1991a.

[55] Weitzman, 1992:363.

[56] What this might mean is discussed in some detail in Section 3.3 of this paper.

[57] Gatsios and Seabright, 1989; Geroski, 1989; Cowan, 1991a; Llerena and Llerena, 1993.

[58] David and Rothwell describe this tension between uniformity and diversity as a problem of positioning on a scale from 'order' to 'freedom' (1996).

[59] David and Rothwell, 1996.

[60] Dosi, 1992. Cohendet, Llerena and Sorge (1992) point out that, without some capacity for learning, the maintenance of options - and thus diversity - can be of no value at all.

[61] Cohendet, Llerena and Sorge, 1992.

[62] After all, "[f]or senior managers at the corporate headquarters of most large firms, diversity is a fact of life" (Goold and Campbell, 1986:3). In commercial terms, the task is not to document the (rather obvious) existence of diversity, but to provide tools for its more systematic exploration and exploitation.

[63] Eg: the relative failure of diverse US (compared with standardised French) nuclear power reactor design traditions (David and Bunn, 1996).

[64] A good example is provided in the case of policy making concerning the UK nuclear industry during the privatisation of the national electricity supply industry in the late 1980's and early 1990's (cf: Stirling, 1994, 1996).

render the concept highly vulnerable to rhetorical use in industrial or institutional special pleading [65]. Given this, and the prominence of diversity in so many important and topical areas of policy making, it is surprising that - compared to the analysis, for instance, of environmental [66] or scale [67] externalities - relatively little effort has been devoted to detailed or systematic exploration of the nature and implications of economic (and especially technological) diversity. Whatever view might be taken on the overall merits of the case for diversity, there is a serious need for the development of transparent, flexible and robust techniques for the 'mapping' of economic diversity in different dimensions and under different circumstances [68].

Before turning to examine these critical questions more closely, however, there remain a number of other dimensions to the wider role of diversity in the economy. These concern the strategic response to intractable uncertainties and ignorance about the future, the tendency for markets to become 'locked-in' under increasing returns and the increasing imperative towards the accommodation of divergent rationalities and value systems in modern plural societies. Each of these issues carries potentially important implications for the characterisation of economic diversity and the trade-off that might be struck with standardisation. Each will therefore be examined in turn.

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[65] Recognising this, Matthews and McGowan urge that "care must be taken that arguments in favour of diversity are not used opportunistically by those seeking (via political mechanisms) to protect particular firms and industries. This is precisely why we need to be as rigorous as possible in our assessment of the benefits of diversity in *particular* technological areas" (1992).

[66] Commented on in relation to the Energy sector in Stirling, 1994. For comparable reviews of economic analyses of environmental externalities in this area, see Stirling, 1992; 1997.

[67] Commetned on in Matthews and McGowan, 1992.

[68] Bruno, Cohendet and Desmartin, 1991.

1.2 Hedging Against Ignorance

It has been mentioned that diversity is widely seen in economics as a 'resource pool', conferring 'resilience' in the face of 'incertitude' [69]. This is a potent idea, holding implications that transcend questions of innovation, competition and economic growth. Indeed, dilemmas loosely labelled as 'uncertainty' are fundamental to many other areas of economics, management and policy analysis. In all these areas, the notion of the 'resource pool' might more specifically (after Breznitz [70]) be seen as a 'response pool' - the retention of a capacity to pursue alternative strategies should circumstances change [71]. Yet, though it may seem intuitively appealing, such a formulation raises a number of issues. Perhaps foremost amongst these is the question of how diversification relates to the many sophisticated alternative approaches to decision making in the absence of certainty. In particular, given the well-established status of probabilistic techniques, the question might be, "what additional value is offered by a separate approach to the strategy of diversification that is not already offered by methods such as expected utility maximisation and portfolio theory?"

In seeking to answer such a question, the starting point must be an examination of the degree to which probabilistic techniques actually address the *full* character of incertitude in the real world. Over recent years, the epistemological basis for a 'realist' interpretation of the notion of probability has come under increasing doubt [72]. Where there exist credible grounds for the assignment of a discrete probability to each of a well-defined set of possible outcomes, then a decision-maker (or process) faces the paradigm conditions of *risk* **[73]**. Classically, this may be taken to reflect established frequencies of occurrence of similar past events under comparable circumstances (or in a hypothetical series of trials). Where outcomes can be fully characterised under a single metric, then probabilities may be expressed as a continuous density function over the chosen scale. Box 2 illustrates the four fundamental categories of 'incertitude' which are implied by this twofold distinction between 'knowledge about likelihoods' and 'knowledge about outcomes' which is central to the probabilistic conception of 'risk'. In the case of 'risk' itself (in the strict sense), then, we are in the top left-hand corner of the top left hand quadrant of Box 2.

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[69] Eg: Llerena and Llerena (1993) and Grabher and Stark (1997) cited above. For reasons of clarity that will become clear in the discussion below, the present author favours the use of the term 'incertitude' in a general overarching fashion which subsumes both 'risk' and 'uncertainty' in the strict senses of these terms as defined below (Stirling, 1994).

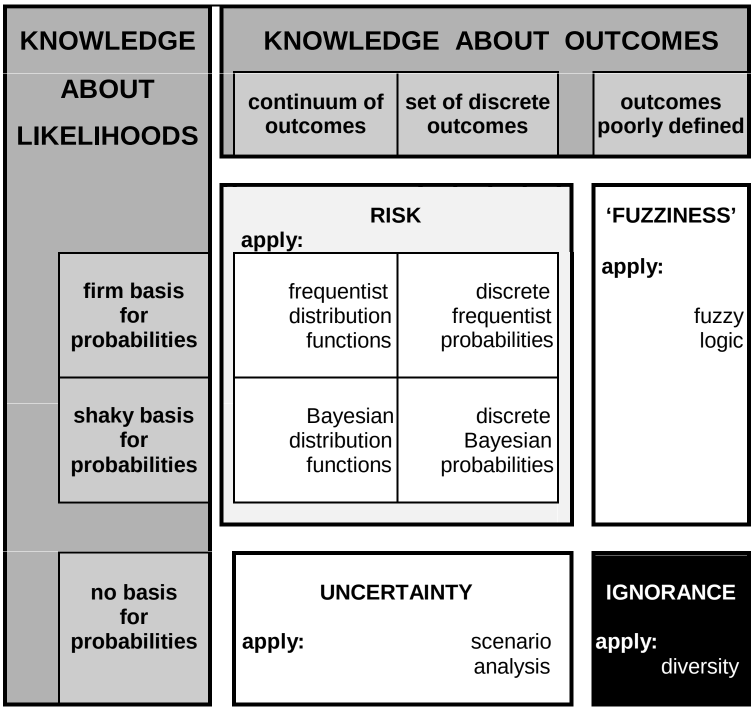
[70] Breznitz (1985) cited in Brooks, 1986:340.

[71] Brooks characterises this as a form of Breznitz's 'behavioural insurance', involving "the repertory of behavioural responses on which they draw to meet the challenges presented by their environment" (Brooks, 1986).

[72] A trend recognisable in Hacking, 1975; Weatherford, 1982; Szekely, 1986; Watson, 1994; Porter, 1995.

[73] After Knight, 1921. See also Luce and Raiffa, 1957. This is sometimes referred to (eg: Rosenberg, 1996:340) as 'Arrovian uncertainty' (cf: Arrow, 1974b) to distinguish it from the 'Knightian uncertainty' described below and in Box 2.

Box 2: A formal scheme for the definition of ‘risk’, ‘uncertainty’ and ‘ignorance’



Unfortunately, exclusively ‘realist’ or ‘frequentist’ probabilistic understandings of incertitude are open to serious doubts concerning the comparability of past and future circumstances and outcomes. The concept of a hypothetical series of trials is singularly inappropriate in cases where the decisions in question are large in scale or essentially unique, take place in a complex and rapidly changing environment or involve effectively irreversible impacts. Where the different aspects of performance are many in number and incommensurable in form, attempts to reduce this to a single metric further compound the difficulties. In disciplines such as financial investment appraisal, the existence of short time horizons and a dominating monetary ‘bottom line’ are often held to supersede such difficulties and justify the imposition of a single numeraire [74]. Yet, in fields such as industrial strategy, policy analysis and technology assessment, these issues of scale, novelty, uniqueness, complexity, change, irreversibility and incommensurability are manifestly the norm and cannot so readily be set aside. In a strict ‘frequentist’ sense, then, techniques based on probability theory are quite simply inapplicable to many of the most important decisions that take place within the economy. In these contexts at least (in the words of de Finetti), “probability does not exist” [75].

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[74] Cf: Simha, Hemalatha and Balakrishnan, 1979; Lumby, 1984; Brealey and Myers, 1988. Yet, even in the field of financial management, it is evident that probabilistic approaches are more prominent in teaching and academic research than they are in real fund management strategies (Myers, 1984). See also: Malkiel, 1989.

[75] De Finetti (1974) quoted in Morgan et al (1990:49)

Of course, the usual response to this familiar predicament is to adopt some more openly subjective ‘Bayesian’ perspective and regard probabilities as an expression of the ‘relative likelihoods’ of different eventualities, given the best available information and the prevailing opinions of specialists [76]. Yet, even this more modest approach requires heroic aspirations to complete information and exhaustive analysis concerning all possible options, outcomes and prior circumstances [77]. The form of a probability distribution is often as important as its mean value or its variance. Where differing irregular or asymmetric probability density functions overlap, then even an ordinal ranking of options can be indeterminate [78]. In short, a ‘Bayesian’ extension of the probabilistic paradigm exchanges the positivistic hubris and restrictive applicability of the frequentist approach for enormous sensitivity to contingent and subjective framing assumptions. Under a Bayesian approach, narrowly divergent (but equally reasonable) inputs may yield radically different results.

Where these difficulties are recognised, a decision-maker (or process) confronts the condition of *uncertainty* in the strict sense introduced originally by Knight [79]. Here, we are in the lower left-hand quadrant of Box 2. This is a situation where it is possible to define a finite set of discrete outcomes (or a single continuous scale of outcomes), but where it is acknowledged that there simply exists no credible basis for the assignment of probability distributions. Although advocates of probabilistic approaches sometimes reject this distinction between situations where probabilities are ‘knowable’ and those where they are ‘unknowable’ [80], such opposition often seems motivated more by a sentimental attachment to the facility and elegance of probability calculus than by any refutation of the practical depth and scope of incertitude in the real world [81]. Whatever the intent, the continued advocacy of techniques such as portfolio theory or expected utility maximisation under conditions of strict uncertainty can have the effect of introducing confusion over terminology [82] fostering quite fundamental misconceptions amongst non-specialists over the applicability and rigour of probabilistic approaches. Indeed, the general treatment of uncertainty as if it were mere risk offers a prime example of what Hayek once lamented as the “pretence at knowledge” in economics [83].

Serious as they are, these difficulties are unfortunately only a part of the problem faced in the ‘economics of incertitude’. For the formal definitions of risk and uncertainty imply two further complementary conceptual categories (the right hand column in Box 2). One is directly analogous to the condition of ‘fuzziness’, under which the various possible outcomes do

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[76] Jaynes, 1986; Wallsten, 1986.

[77] Collingridge, 1982:22.

[78] Goodman, 1986; Beck, 1987.

[79] Knight (1921), elaborated usefully many times since, eg: Luce and Raiffa, 1957.

[80] The phrasing is that of Luce and Raiffa (1957).

[81] For instance, on the somewhat expedient grounds that the distinction “serves little purpose” (Lumby, 1984:108), since it renders “the theory of probability virtually inapplicable to real world decision making, outside games of chance involving dice or cards” [Morgan et al (1990:49)]. Discussions of uncertainty tend all-too-often to be framed in terms of the available techniques, rather than the nature of the problems themselves (eg: Andrews, 1995).

[82] For instance, with the terms ‘risk’ and ‘uncertainty’ used interchangeably (eg: Lumby, 1984:108) with their designations conflated to mean the general “absence of certainty” (McKenna, 1986:9).

[83] This was the title of his Nobel Memorial Lecture delivered in 1974 (Hayek, 1978:23).

not admit discrete definitions, but where the degree to which they are actually manifest can be expressed in numerical terms akin to the assignment of probabilities (the top right quadrant of Box 2) [84].

Of greater significance for present purposes, however, there is the condition that has been dubbed *ignorance* [85]. This is a state under which there exist neither grounds for the assignment of probabilities, *nor* even a basis for the definition of a comprehensive set of outcomes (the lower right hand quadrant in Box 2). Such a situation may arise for instance, where analysis is defied by the sheer number of permutations generated by a variety of incommensurable performance criteria, each defining a scale of possible states [86]. It emerges especially in complex and dynamic environments where agents may themselves influence (in indeterminate ways) supposedly exogenous 'events' [87] and where the very identification of particular courses of action can exert a reflexive influence on the appraisal of alternatives. Though it may be described variously as 'epistemological' or 'ontological' in character [88], or 'substantive' or 'procedural' in form [89], this broad concept of 'ignorance' is nevertheless of considerable practical importance [90]. It arises from many familiar sources, including incomplete knowledge, contradictory information, data variability, conceptual imprecision, divergent frames of reference and the intrinsic indeterminacy of many natural and social processes [91]. Put at its simplest, ignorance is a reflection of the degree to which "we don't know what we don't know" [92]. It is an acknowledgement of the importance of the element of 'surprise' (whether positive or negative in nature) [93] - emerging not just from the actuality of unexpected events, but from their very possibility [94].

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[84] The author is grateful to David Fisk for a conversation concerning the status of fuzzy logic under this scheme. Where categories of 'outcomes' are conceived in terms of set theory, the assignment of 'fuzziness' in Box 2 rests on an analogy for members of outcome sets between 'probabilities of eventuation' and 'degrees of set membership', both of which are expressible as numerical weightings normalised to sum to unity. Cf: Klir and Folger, 1988; Dubois, et al, 1988; Zadeh and Kacprzyk, 1992; Kosko and Isaka, 1993 and Smith, 1994a, 1994b.

[85] For various perspectives, cf: Shackle, 1968; Loasby, 1976; Collingridge, 1982; Ford, 1983; Smithson, 1989; Faber and Proops, 1994. The waters are rather muddied by the use of the term 'ignorance' in rather different contexts and with even more divergent implications, (cf especially: Shackle, 1968; Ford, 1983) and Dempster-Shafer theory (Yager, 1992).

[86] As argued by Rosenberg (1996:340): "If uncertainty exists along more than one dimension, and the decision maker does not have information about the joint distribution of all the randon variables, there is little reason to believe that a 'rational' decision is possible or that there will be a well-defined 'optimal' investment of adoption strategy".

[87] Dosi and Egidi, 1987.

[88] See Winkler (1986) and other essays in Winterfeldt and Edwards, 1986. Also: Rosa, 1998.

[89] Although discussed in relation to the term 'uncertainty', Dosi and Egidi's (1987) distinction applies also to what is here termed 'ignorance'.

[90] There is an enormous number of different schemes for categorising the various forms and sources of incertitude. For useful reviews see especially: Smithson, 1989; Morgan, Henrion and Small, 1990; Rowe, 1994; Faber and Proops, 1994.

[91] Thompson and Warburton, 1985; Winkler, 1986; Wynne, 1987; Morgan, Henrion and Small, 1990; Funtowicz and Ravetz, 1990; Schwarz and Thompson , 1990.

[92] Reflecting the well worn aphorism attributed to Pliny to the effect that "the only certainty is that nothing is certain" (Pliny the Elder, 25-79 CE, *Historia Naturalis*, Book II, 7 – cited in Morgan and Henrion, 1990:*title page*). Ignorance reflects our uncertainty about our uncertainty (cf: Cyranski, 1986).

[93] Brooks, 1986. Perhaps because of the pejorative or pessimistic overtones of the term 'ignorance', there seems in some quarters to be a somewhat greater readiness to formulate the problem as one of 'surprise' (eg: Schneider, Turner and Garriga, 998). Perhaps for the same reason, numerous authors use adjectives such as 'partial' to qualify the term 'ignorance'. However, the present author believes that 'surprise' is a bad generic term for the condition itself, because it refers to the state of knowledge *after* the manifestation of developments rather than *before* and is therefore (unlike 'ignorance') inconsistent with the concepts of 'risk' and 'uncertainty'. Likewise, since - in the terms set out in Box 2 – the concept of ignorance is a precise complement for the concepts of 'risk', 'uncertainty' (and, perhaps, 'fuzziness') which are also available to describe aspects of a real-life state of knowledge, it seems that the term 'ignorance' no more needs qualifiers than does the term 'risk'.

[94] Dosi and Egidi, 1987. One topical example of the growing acknowledgement of ignorance in relation to market regulation and technology choice is provided by the increasingly widespread acceptance of a need for a 'precautionary principle' in environmental policy (eg: Wynne, 1992; O'Riordan and Cameron, 1994; Dovers and Handmer, 1995).

Concrete examples of the state of ignorance (rather than 'risk' or 'uncertainty') typically associated with technological and institutional innovations are almost too numerous to mention. It is hardly necessary to belabour the point that, wherever large-scale technological infrastructures have been adopted, they have given rise to unintended (and initially unforeseen) environmental consequences [95]. Examples include fossil fuel combustion, nuclear power production, automobile transportation, agricultural pest management, aerosol propulsion by CFC's and thermal insulation by asbestos. Similarly, one does not have to invoke technological determinist reasoning [96] to acknowledge that (although the technologies themselves are undoubtedly 'socially shaped') the adoption of innovations such as the automobile, the telephone, radio and television and oral contraceptives exert profound, contingent and largely unforeseen countervailing influences on the societies in which they are embedded [97]. The unforeseeable character of the political impacts of the internet or the environmental and health impacts of genetic modification in agriculture are examples of the types of ignorance which are increasingly recognised by sociologists as key ordering principles in the social relations, institutional structures and political discourse of the emerging 'risk society' of contemporary 'high modernity' [98]. Yet it is not only modern technological infrastructures which invoke ignorance of this sort. The consequences of individual processes of animal and plant domestication in prehistory were in principle, *a priori*, no more foreseeable and no less profound in their consequences than are the more recent examples [99]. Whether it be the Catholic Church, the watermill [100], the clock [101], the printing press, the Reformation or the postal system, history is littered with interlaced instances of the advent of seminal technological or institutional innovations with unforeseeable contingent consequences. Nor, of course, are such 'surprises' always negative. Rosenberg points out in some detail with reference to the steam engine, the telephone, the radio and the laser that ignorance can arise as much in a failure to predict positive consequences as to not foresee negative impacts [102]. Just as "… the uncertainties associated with the eventual uses of the laser or the computer might more appropriately be characterised as ignorance rather than uncertainty" [103], so too it would be a brave analyst indeed who seriously proposed the use of probabilistic techniques as a means to characterise the unintended and unforeseeable consequences of institutional and technological innovations such as those mentioned here.

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[95] Cf: Tenner, 1996.

[96] Cf: White, 1962; Weatherford, 1991.

[97] The relationship between technology on the one hand and institutions, social relations, power and culture on the other is an enormous field which it is not the purpose to summarise here. An attempt is made elsewhere in this regard by the present author (Stirling, 1994). Some of the principal perspectives are set out in detail in: Winner, 1977; Hughes, 1983; Winner, 1986; Callon, Law and Rip, 1986; Yearley, 1988; Elliott, 1988; MacKenzie, 1990; La Porte, 1991; Webster, 1991; Bijker and Law, 1992; Summerton, 1994a; Bijker, 1995; Sclove, 1995; MacKenzie, 1996; Rip, Misa and Schot, 1996 and Ingelstam, 1996. For an excellent recent review of some of this material, see Williams and Edge, 1996.

[98] Giddens, 1991; Beck, 1992; Beck, Giddens and Lash, 1994; Lash, Szerszynski and Wynne, 1996; Beck, 1996.

[99] A theme touched on in Stirling, 1984. See also essays in Lemonnier, 1993.

[100] Creswell, 1993.

[101] Bedoucha, 1993.

[102] In the 1870's, telegraph companies resisted pursuit of telephone patents, Marconi initially viewed radio as a tool for point-to-point communication rather than broadcasting and Bell Labs were initially reluctant to patent the laser because of a perceived lack of possible applications (Rosenberg, 1996). Conversely, of course, there are at least as many examples where optimistic market expectations have failed to materialise (eg: Concorde).

[103] Rosenberg, 1996:340.

When conceived of in this way, it is clear that the condition of ignorance is all-pervasive. It affects our personal lives [104], our politics, our culture and our science as much as it does our technologies, institutions and economic systems. It is, however, particularly pronounced in the consideration of large scale, long-lived, slow-to-develop or politically sensitive actions, such as long-term innovation programmes, infrastructure investments or policy initiatives. Crucially, ignorance is neither the simple inverse of knowledge nor the linear 'zero-sum' complement of what is 'known'. Rather than being thought of as the 'residual' remaining after all that is known has been accounted for, ignorance may instead be seen partly as an independent condition in its own right. Indeed, there is an important sense in which ignorance may actually be seen to increase with the accumulation of knowledge [105]. Although complex and sometimes counterintuitive, these insights concerning the relationship between ignorance and knowledge are far from new. Some twenty-three centuries ago, the Chinese philosopher Lao Tzu neatly summed up the reflexive character of the interaction between 'knowledge' and 'ignorance' when he recognised that "knowing ones ignorance is the best part of knowledge" [106].

The point is of course, that, to an extent even greater than is the case with strict uncertainty, the condition of ignorance is not tractable to the 'puzzle solving' strategies of probability theory [107]. Although the more optimistic of Bayesian theorists may debate the applicability of probabilistic techniques under strict uncertainty, there can be no question that they are applicable under ignorance. Indeed, since (by definition) the full range of possible outcomes is itself indeterminate, the condition of ignorance is not even susceptible to treatment by qualitative scenario analysis or simple outcome-based decision rules (such as so-called 'maximax' and 'maximin' criteria [108]). When formulated in this way, in terms that are consistent with - and implied by - the fundamental foundations of probability theory, the importance of ignorance seems obvious. However, aside from the activity of a small minority of researchers [109], the vast bulk of theoretical and practical work in decision analysis and the economics of uncertainty makes virtually no reference even to the existence - let alone the importance – of this condition of ignorance [110]. The comments cited earlier in discussing the rejection of the concept of strict uncertainty suggest that this attitude coincides with a positivist attitude to knowledge. However, Lao Tzu's insight

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[104] Indeed, contrary to some axiomatic assumptions in rational choice theory, individuals may often be unsure even of their own personal motivations, intentions and preferences (Tversky and Kahnemann, 1974; Hammond, McLelland and Mumpower, 1980).

[105] Ravetz, 1986; Wynne, 1992.

[106] Lao Tzu (c.300 BCE), '*Tao te Ching*', No.71 cited in Morgan and Henrion (1990:1).

[107] The distinction between 'problems' and 'puzzles' is borrowed from Kuhn (1970) and applied in this context by Funtowicz and Ravetz (1990). In other words, ignorance cannot be treated in terms of "mathematical formalisms … as if it were an additional physical variable" (Funtowicz and Ravetz, 1989:621).

[108] 'Maximin', 'minimax regret', 'Laplace', 'maximax 'and 'Hurwicz' decision criteria are all predicated on an ability to identify a complete set of possible outcomes and distinguish between them (Pearce and Nash, 1981).

[109] For their part, for instance, Dosi and Egidi acknowledge that under what is here termed the condition of ignorance in economics, "the normal axiomatic theory of choice is neither a approximate nor a legitimate theoretical stylisation" (1987:15). Others who have focused in one way or another on the problems of ignorance include (broadly within economics): Shackle, 1968; Loasby, 1976; Ford, 1983; Faber and Proops, 1994; Schelling, 1995 and Rosenberg, 1996 (and outside economics): Holling, 1973; de Finetti, 1974; Collingridge, 1980, 1982, 1983b; Ekeland, 1984; Ravetz, 1986; Hacking, 1986; Brooks, 1986; Klir, 1989; Smithson, 1989; Allen and Lesser, 1991; Dohnal, 1992; Wynne, 1992; Stirling, 1994, 1998; Hogarth and Kunreuther, 1995; Dovers and Handmer, 1995.

[110] A fairly random selection of specialist books drawn from various fields concerned with the analysis of incertitude which neglect discussion of the condition of ignorance (as defined here) are as follows: Knight, 1921; Keynes, 1921; Carnap, 1950; Keeney, Raiffa and Meyer, 1976; Alder and Rossier 1977; Pearce and Nash, 1981; Lumby, 1984; Hogwood and Gunn, 1984; Winterfeldt and Edwards, 1986; McKenna, 1986; Brealey and Myers, 1988; Morgan, Henrion and Small, 1990; Lutfiyya, 1991; Zadeh and Kacprzyk, 1992; Suter, 1993. The condition of ignorance generally receives even less attention in textbooks and more popular treatments of decision making under incertitude than it does in this more specialist literature.

quoted above suggests the opposite. If it is accepted that the acknowledgement of ignorance is a prerequisite for knowledge, then any ostensibly positivistic denial or neglect of this condition becomes identifiable as being actually antithetical to a *true* respect for knowledge.

Since the reluctance to acknowledge the full implications of ignorance seems to stem in part from a pragmatic desire to apply operational analytical techniques to incertitude [111], it is curious that relatively little attention has been given to the development of formal non-probabilistic strategies for decision-making under ignorance. It is not as if such approaches are inconceivable. The securing of 'option contracts' is a practice which pre-dates the formulation of probabilistic approaches [112] and which may be pursued without the use of such techniques [113]. Inter-related concepts such as flexibility, resilience, robustness, stability, modularity and redundancy are all - in different contexts - advanced as part of a systematic response to the condition of ignorance [114]. Arguably foremost amongst the battery of such approaches, however, is *diversification*. Of all the strategies available for responding to strict uncertainty and ignorance, this is the only one that has been elevated to the status of a figure of speech. No matter how great the resources, nor how complete the knowledge, nor how sophisticated the decision making process, only fools put all their eggs in one basket [115]. The question is thus raised as to whether diversification may offer a basis for a decision heuristic under strict uncertainty and ignorance which is potentially superior to the elaborate - but formally inapplicable - armoury of probability theory.

In contemplating diversification as a means to mitigate the effects of strict uncertainty and ignorance, a crucial shift of attention is taking place: away from an emphasis on analytical attempts to characterise the 'problem' and towards a more direct focus on one of the possible 'solutions' [116]. Such an approach relies for its appeal on the inherently greater tractability of the task of characterising the operational attributes of the available options, as compared with the task of characterising the nature and relative likelihood of all possible future states of the world [117]. Accordingly, in addition to the areas of innovation, competition and growth already reviewed, a strategy of deliberate diversification is variously pursued in fields as disparate as investment management [118], regional development, systems engineering [119], gambling [120], intelligence gathering and energy policy [121]. In the particular context of technology policy, the conclusions recently reached by Rosenberg are worth recording in full.

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[111] Eg: Andrews, 1995.

[112] Ed Steinmueller, SPRU, *pers comm,* May 1998.

[113] Eg: David, Mowery and Steinmueller, 1988.

[114] Cf: May, 1972; Holling, 1973, 1994; Prigogine, 1980; Jantsch, 1980; Allen, 1994; Norgaard, 1994; Genus, 1995; Norton, 1995; Farber, 1995; Killick, 1995; . Pimm (1984) develops a systematic scheme of definitions for some of these concepts.

[115] This proverb is extremely widespread and may be traced back in Europe for several hundred years (Simpson, 1992).

[116] Stirling (1994) addresses this in the context of energy policy. As has long been recognised in artificial intelligence, diversification as a problem solving response, rather than a way of reasoning about ignorance (Cohen, 1985).

[117] Eg: Stirling, 1994.

[118] Eg: Lumby, 1984.

[119] Eg: Cohen, 1985.

[120] Cohen, 1985:20.

[121] Stirling, 1994, 1995.

> "The pervasiveness of [strict uncertainty and ignorance] suggests that the Government should ordinarily resist the temptation to play the role of a champion of any one technological alternative, such as nuclear power, or any narrowly concentrated focus of research support, such as the War on Cancer. Rather, it would seem to make a great deal of sense to manage a deliberately diversified portfolio that is likely to illuminate a range of alternatives in the event of a reordering of social or economic priorities or the unexpected failure of any single major research thrust" [122].

Although adopted in technology policy for just such reasons, the pursuit of deliberate diversification has nowhere been more prominent than in the field of energy policy. Much of the discussion in this area provides a practical illustration of aspects of a diversification strategy which are of relevance in other institutional contexts. In the Energy Sector, diversity is widely seen to "provide greater strength in guarding against unforeseen events" [123]. It does this by "… reducing the potential impact of interruptions in any single source and by providing additional options for its replacement" [124]. In systems that are subject to the exercise of monopoly influence, diversity offers a means not only to mitigate, but also to deter, unfair, disruptive or otherwise adverse actions [125]. Of course, in addition to its value in reducing negative impacts, diversity also offers a means to foster opportunities to take advantage of unforeseen positive developments [126]. It is a way of retaining *flexibility* across a system as a whole, by "trying for the best, risking the worst and being ready to reverse a decision should the worst occur" [127]. Although not without their problems [128], analogies with the relationship between biodiversity and ecological integrity are, for their part, taken to suggest that economic diversity might in this way be seen as a means to promote *resilience* [129], by conferring a "property that allows a system to absorb changes and still persist" [130].

Whatever the benefits of diversity in mitigating ignorance however (just as with the promotion of innovation and growth), the real challenge lies in identifying the trade-offs between diversity and other measures of performance [131]. As Brooks observes, "[a]n overall system that is less efficient or more costly because it requires the infrastructure for a diversity of technologies may nevertheless have greater viability or survival potential in an environment subject to shocks and surprises

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[122] Rosenberg, 1996:352.

[123] Kaijser, Mogren and Steen, 1991:140.

[124] IEA, 1985:90.

[125] By reducing the potential exposure of a target system, an action may be rendered less attractive to the perpetrator. Stirling, 1994 compares Willrich 1975 and IEA, 1985.

[126] Brooks, 1986.

[127] Collingridge, 1983a:162

[128] Namely the confusion that often exists between the services conferred by *biomass* and those due to the more precisely defined property of *biodiversity* (Myers, 1996). Likewise, there are problems with relatively simplistic arguments that biodiversity confers stability in ecosystems. More sophisticated discussions of this relationship distinguish static and dynamic stability and local and global diversity (Norton, 1987). The position taken ultimately boils down to a question of definition of these and other terms, cf: May, 1972; Goodman, 1975 and, especially: Pimm, 1984.

[129] As argued by Llerena (Llerena and Llerena, 1993) already cited.

[130] Holling, 1978. Described alternatively by Myers as "… homeostatic attributes that allow [the system] to maintain function in the face of stress-induced structural change" (Myers, 1996).

[131] Cohen is explicit about diversification as a way of trading away uncertainty against other desirable qualities (Cohen, 1985).

or discontinuities in long term trends" [132]. The value of this trade-off will, in part, be a reflection of the 'aversion to ignorance' on the part of a decision maker in any particular context. The greater the confidence in the robustness of performance appraisal results for the individual options (all else being equal), the lower will be the value of diversity in a portfolio of options taken as a whole.

Against this background, it seems even more curious that so little attention has been devoted to the development of rigorous and systematic ways of thinking about diversification among economic options. This relative dearth of attention is particularly pronounced when set against the scale of activities in developing and applying probabilistic techniques [133]. Indeed, in considering the value of diversity as a strategy against intractable uncertainties in artificial intelligence (AI), Cohen holds that "[o]ne may speculate that AI uses quasi-probabilistic numerical methods for reasoning under [strict] uncertainty less for any advantages of normative reasoning than for lack of other methods" [134]. This pithy observation seems as acute in the field of economics as it is in AI. If it is true that the perception of a lack of alternatives is driving the use of techniques of probability theory in addressing problems of strict uncertainty and ignorance to which they are (by definition) not applicable, then the imperative for the development of robust and rigorous non-probabilistic approaches to the analysis of economic diversity is further strengthened.

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[132] Brooks, 1986.

[133] Indeed, it is really only under the auspices of probability theory - in the techniques of portfolio theory (such as the 'capital asset pricing model') - that formal attention has been directed at the characterisation of diversity (cf: Simha, Hemalatha and Balakrishnan, 1979; Lumby, 1984; Brealey and Myers, 1988). Here, of course, the problem is that probabilistic techniques are, by definition, inapplicable under the condition of ignorance to which diversification itself is a response.

[134] Like the present account, Cohen sees the role of diversity as emerging most clearly when the issue is framed as a problem of reasoning *about* uncertainty, rather than the more traditional 'reasoning *under* uncertainty' (Cohen, 1985:9).

1.3 Mitigating Lock-in

This paper has so far discussed two distinct sets of reasons for examining the role of diversity in the economy: on the one hand, concern to foster beneficial forms of technological innovation and economic growth, and on the other, the difficulties of decision making under strict uncertainty and ignorance. Before focusing on a final possible rationale for diversification, attention should turn briefly to some powerful social and economic mechanisms which militate *against* technological (and associated institutional) diversity.

The first is the phenomenon of ‘positive feedback’ [135]. Whilst orthodox economics has tended to focus on equilibrium processes operating through diminishing returns, countervailing forces of increasing returns have been recognised at least since Mill [136] and have emerged intermittently in the literature since then [137]. The picture has been significantly clarified by work in the economics of technology over recent years. Processes such as Arrow's "learning by doing" [138], Rosenberg's "learning by using" [139] and Sahal's "learning by scaling" [140] have all been shown to play an important role in technological development. Combined with other ‘positive network externalities’ [141], such processes render the diffusion of modern, complex, infrastructure-based technologies subject to powerful ‘increasing returns to adoption’ [142]. The work of Arthur, in particular, has shown in some detail how, under these conditions, the unfolding of important technological choices over time may display the property of ‘path dependency’ [143]. Rather than being subject to global equilibrium, outcomes may often prove highly sensitive to contingent, arbitrary and even apparently trivial influences during their early development or dissemination [144]. Arthur shows in general terms how increasing returns to adoption may lead to markets becoming ‘locked in’ to what might (in the long run) be less efficient choices [145].

In essence, the phenomenon of increasing returns to adoption is simple. The more an option is chosen, the more attractive it will become. Of two competing options which become available at the same time, one may have more favourable initial performance but a small potential for incremental improvement, whilst the other may have a relatively poor initial performance but hold out the prospect of far more rapid subsequent advance. Making reference to a well known fable,

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[135] Arthur, 1988, 1990a.

[136] Carlsson and Jacobsson, 1995.

[137] Notably in the works of Robinson (eg: 1933).

[138] Arrow, 1962.

[139] Rosenberg, 1982.

[140] Sahal, 1985.

[141] Such as consumer expectations of reduced uncertainty, increased flexibility and lower transaction costs associated with a choice of option which is expected to become dominant on the network in question (Cowan, 1991a).

[142] Arthur, 1989a.

[143] Eg: Arthur, Ermoliev and Kaniovski, 1987; Arthur, 1989a.

[144] A condition known associated technically with the property of ‘nonergodicity’ (Arthur, Ermoliev and Kaniovski, 1987). This is a property under which a system tends to reside in only a subset of all possible states.

[145] Arthur, 1988, 1989, 1990a.

Cowan terms such options "hares" and "tortoises" respectively [146]. Examples are legion of markets locking-in to ‘hares’ rather than the long-run superior ‘tortoises’ [147]. Arthur cites as candidates: narrow gauge British railways [148], US colour television standards and the computer programming language FORTRAN [149]. David establishes the classic case of the inefficient ‘QWERTY’ structure for the conventional typing keyboard [150]. The success of the VHS home video format over apparently superior configurations is another much-cited example [151]. David and Bunn explore the dominance of alternating current in electricity supply systems [152]. Cowan himself examines the establishment of the family of ‘light water’ designs for nuclear power reactors [153]. Indeed, Arthur even speculates that, had it not been for a series of small scale contingencies and the action of dynamic increasing returns in the late nineteenth century, the present ascendancy of the internal combustion engine might have been substituted by an alternative automobile motor derived from the steam engine with equal (or superior) overall long-run performance [154].

Of course, none of these examples are conclusive evidence for the dominance of increasing returns mechanisms in any particular instance [155]. Since much of the argument necessarily rests on judgements concerning the relative merits of paths *not* taken, such evidence would by its very nature be intrinsically difficult to gain. However, simply by taking account of something as simple and as obvious as positive feedback, recognition even of the possibility of ‘path dependency’ and ‘lock in’ raises serious questions over the automatic assumption that market mechanisms will ensure long run efficiency in technological choices. When attention turns to more complex institutional and sociological processes, the picture is further compounded. Seminal events in the early development of a technological market may be apparently minor in scale, yet far from ‘contingent’ or ‘arbitrary’ in origin. For instance, "strategic action" by "sponsoring firms" might be directed at reinforcing the effects of increasing returns to adoption [156]. By techniques such as "penetration pricing", firms may exchange losses early on for potential monopoly profits at a later stage. Likewise, the political and commercial processes involved in standard-setting may fulfil a crucial role in promoting certain favoured options. Although early trends in patterns of adoption are modelled by Arthur as a random walk, he acknowledges that deliberate actions may play a determining role[157]. In such cases, he says, "the random walk drifts" [158]. In this way, recognition by economists of the role

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[146] Cowan, 1991b. Also Cowan, 1991a.

[147] A useful overview is presented in OECD, 1992.

[148] After Kindleberger, 1983.

[149] Arthur, 1989a.

[150] David, 1985. This example is criticised by Liebowitz and Margolis (1990).

[151] Arthur, 1990. The example is taken as a basis for a criticism of the inceasing returns concept in Liebowitz and Margolis, 1995.

[152] David and Bunn, 1988.

[153] Cowan, 1990.

[154] Arthur, 1989:126.

[155] Individual assessments of the relative merits of light water and gas-cooled reactors, VHS and Betamax videos and even QWERTY and alternative keyboard designs are all open to challenge. For instance, Liebowitz and Margolis (1990, 1995) criticise the increasing returns literature on both empirical and theoretical grounds.

[156] Arthur, 1989a:123.

[157] Arthur sees this as a question of the "behaviour of key personages" (1989:126). He discusses in this regard the early role of the US Navy in the configuring of the major nuclear fission reactor design traditions.

[158] Arthur, 1989a:123.

of path dependency and lock-in under increasing returns highlights the potentially enormous sensitivity of technological choices to the deliberate exercise of commercial and political agency [159].

In identifying the potential importance of agency in increasing returns processes, economists are opening the door to a rich body of insights from the history and sociology of technology. There has for many years in these fields been an intense debate over the best way to understand how society goes about choosing technologies and infrastructures in the broadest sense. As has already been touched on in this paper [160], a family of concepts variously termed 'sociotechnical' [161], 'complex technical' [162] or 'large technical' systems [163] and 'actor' [164], 'techno-economic' [165] or 'socio-technical' [166] networks have been identified under a variety of perspectives as the loci of technology choice in society. Despite important differences of emphasis [167], the path-breaking historical work of Hughes [168] and the influential sociological work of Callon [169] and their respective associates, for instance, show (at the highest level of generalisation) how these 'systems' or 'networks' involve not only the firms which manufacture the technological products themselves, nor just their suppliers and large customers, but an extended and heterogeneous array of investors, regulators, unions, professional associations, government departments, research, educational and political organisations. Such systems have poorly defined and fluctuating boundaries, interpenetrating and sometimes encapsulating one another. What remains clear, however, is that each such 'sociotechnical system' is larger than an individual firm, smaller than a commercial sector taken as a whole, but extends horizontally into related sectors and institutions. It possesses some degree of collective self-identity and a sub-culture of ideology and precepts. As such, it pursues a coherent (though not unitary) community of interests, which are distinguishable from those extant in the wider society. Whatever the vocabulary, there is a wealth of empirical historical and sociological material documenting the existence of such 'systems' in areas such as nineteenth century railroads [170], modern "agribusiness", the aerospace industry [171], the "military industrial complex" [172], the automotive and fuel industries [173], information [174] and telecommunications technology [175] health care and pharmaceutical industries [176], and the electricity supply and heavy equipment industries [177].

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[159] The potential effectiveness of such actions will be significantly greater at certain junctures than at others, reflecting the important concept of 'windows of competence' in evolutionary theory (Waddington, 1957).

[160] In Section 1.1

[161] Eg: Winner, 1977.

[162] Eg: Ingelstam, 1996

[163] Eg: Hughes, 1983, 1984, 1986, 1987, 1988, 1994; La Porte, 1991; Gokalp, 1992; Summerton, 1994a; Davies, 1996; Joerges, 1988, 1996.

[164] Eg: Callon, 1986a, .

[165] Eg: Callon, 1991, 1992; Callon, Law and Rip, 1986.

[166] Eg: Bijker and Law, 1992; Bijker, 1995; Elzen, Enserink and Smit, 1996.

[167] Part of the apparent difference between these approaches may be due to the somewhat deliberately hegemonic style of some of the proponents. However, the residual substantive differences are not entirely resolved by attempts informally to negotiate a convention that a 'network' becomes more like a 'system' as a result of a process of 'stabilisation' (de Laat, Callon and Laredo, 1997).

[168] Eg: Hughes, 1983, 1984, 1985, 1986, 1987, 1988, 1990, 1994; Bijker, Hughes and Pinch, 1986; La Porte, 1991; Summerton, 1994a.

[169] Eg: Callon, 1986a, 1991, 1992, 1996, 1997; Callon, Law and Rip, 1986.

[170] Eg: Bucholz, 1994; Usselman, 1994.

[171] Eg: Pinch, 1991; Oster, 1991.

[172] Eg: Kaldor, 1981; Law, 1988, 1992; MacKenzie, 1990, 1996; Rochlin, 1991; Bucholz, 1994.

[173] Grundmand, 1994; Juhlin, 1994.

[174] MacKenzie, 1991.

The essential insight which arises from recognition of these ‘sociotechnical systems’, is that the technological and infrastructural choices which they make may be seen to be *channelled* by a rather narrow set of conditions and considerations. It cannot be assumed that the exercise of these interests will automatically select for optimal performance from the point of view of society as a whole. Indeed, many commentators have explored the mechanisms by which sociotechnical systems exercise what Winner terms "autonomy" with respect to the encompassing society and economy [178]. Many of the most important strategies and mechanisms for this kind of ‘sociotechnical channelling’ have been well recognised for many years. Galbraith (like Ellul before him [179]) highlighted the efforts made by such systems to control markets through vertical integration, monopoly by horizontal expansion and long term contracts (especially with state agencies), paralleled by a shift in power within the firm from shareholders to the executive [180]. Sociotechnical systems tend to favour relatively inflexible commitments of resources, preferring capital intensive investments with long lead times and highly specialised labour. Rather than experimenting with novel techniques, they concentrate on maximising the "load factor" of their established organisational or technological infrastructures [181]. Instead of adapting to changing demands, they seek (by means such as political representation, strategic alliances, regulatory capture, public relations and advertising) to ‘reverse adapt’ demand to suit their favoured conditions of supply [182]. Indeed, through development, assertion and propagation of their own internal "conventional wisdoms", sociotechnical systems may, at the extreme, tend to render certain ideas and options quite literally "unthinkable" in society at large[183]. In short, the technological choices exercised by such sociotechnical systems are held to display ‘momentum’, resisting movement in directions which run counter to the established interests of the various components of the system itself [184].

Though framed more in terms of technological than social or institutional factors, the constrained nature of technology choice in society also arises in the emerging economics of technology. Nelson and Winter identify ‘technological regimes’ [185], by which they mean the "technicians beliefs about what is feasible or at least worth attempting" [186]. Precisely what frame of reference is employed in judging what is "worth attempting" is left largely unexplored, but this is clearly a point of engagement with the sociological literature. In his own elaboration, the economist Dosi also holds the principal

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[175] Webster and Williams, 1986; Schneider, 1991, 1994; Usselman, 1994; Abbate, 1994; Davies, 1996.

[176] Braun and Joerges, 1994.

[177] Hughes, 1983; Thomas and McGowan, 1990; Salsbury, 1991, 1994; Rochlin, 1994; Coutard, 1994, Meier, 1994; Summerton, 1996.

[178] Winner, 1977. Discussion of this seminal concept is encumbered by opposition based on unnecessarily philosophical sophistry concerning the nature of ‘determinism’ (eg: Hughes, 1987:76-80). In identifying the increasing importance of the technological *constraints* on choice, Habermas’ (1968) distinction between ‘technocracy’ and ‘decisionism’ provides one means to resolve this unproductive criticism (cf: Wynne, 1975).

[179] Ellul, 1964.

[180] Galbraith, 1968, 1975.

[181] Hughes, 1987. In more a passive sense - referring to Hirschman’s concept of the ‘hiding hand’ (Hirschman, 1967) - Brooks observes that large incumbent institutions tend to have disproportionate knowledge of the difficulties associated with novel courses of action and are therefore by their very nature inhibited from radical change (Brooks, 1986). See also: Collingridge 1992.

[182] Winner, 1977. Cf: 1980, 1981, 1986, 1996,

[183] Hogwood and Gunn, 1984:172.

[184] Hughes, 1983, 1987, 1994.

[185] Nelson and Winter, 1977.

[186] Nelson and Winter, 1982:57.

determinants of technology choice to lie neither in some inherent or necessary logic of technology, nor in the workings of the market, but in the form and content of the 'technological paradigm' [187]. Again, this explicit use of a concept of social construction is further acknowledgement that it is circumscribed and situated framing assumptions and interests (rather than exogenous or transcendent scientific or market imperatives) which determine the direction of technological innovation. [188]. Finally, in emphasising the inherently constrained nature of actual technological choices in relation to the available range of possibilities, the concept of 'technological trajectories' [189] constitutes an economic perspective on the 'autonomy' or 'momentum' typically displayed in the social choice of technology [190].

Thus translated into the terms of economics, then, the insights from the sociology and history of technology are underscored. The increasing returns to adoption observed to be intrinsic to the economics of technology is, therefore, not simply a neutral property of the market place. Rather it serves as a key strategic feature, both amplifying and itself reinforced by the active agency of market institutions and decision makers. In this sense, structural pre-dispositions towards 'path dependency' and 'lock-in' under increasing returns, as well as 'autonomy' and 'momentum' in 'sociotechnical systems' and conservative 'regimes' and 'trajectories' in technological change, together provide a further potentially important background in examining the importance of technological diversity.

Employing the metaphor of a multidimensional space to represent the many different dimensions in which technological systems may be represented [191], Box 3 provides a schematic illustration of this composite picture. It shows how the particular historic paths that are *actually* taken by technological change tend to be 'channelled' in relation to the full range of unrealised possibilities. They represent only a sub-set of a wider array of alternative 'channels', each corresponding to different historic circumstances and contingent formative events.

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[187] Dosi, 1982

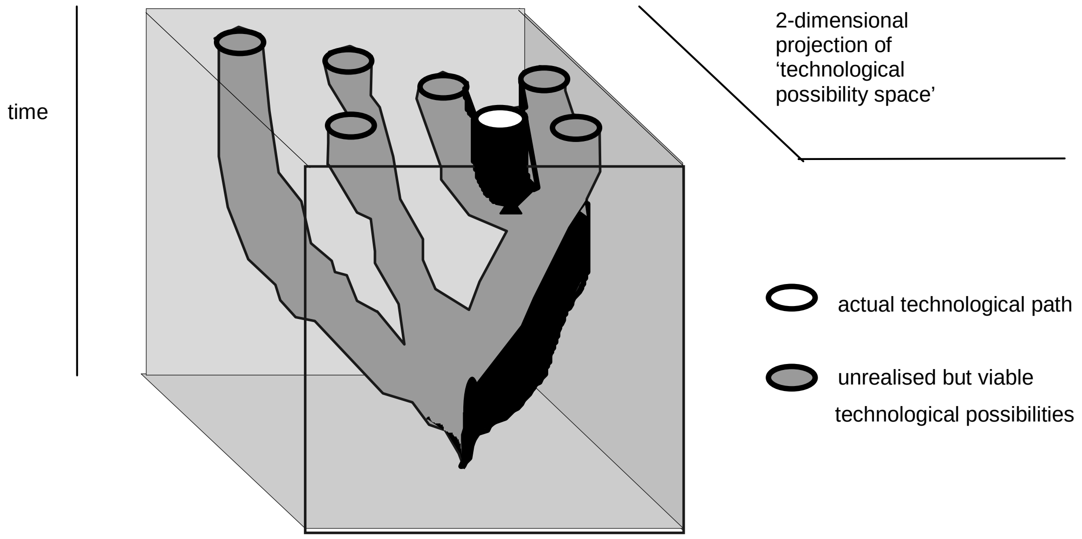
[188] Kuhn, 1970; Clark, 1987.

[189] Dosi, 1982.

[190] Other concepts in the economics of technology which display resonances with this picture include Sahal's 'technological guideposts' and 'innovation avenues' (1985) and Saviotti's notion of homeostasis (1986). These issues are discussed in more detail in Stirling, 1994.

[191] Each dimension metaphorically representing as a parameter some discernible operational feature of the sociotechnical system.

Box 3: A schematic representation of the concept of 'socio-technical channelling'



A number of conclusions flow from this account. First, it has already been noted that probabilistic analysis of incertitude tends to neglect the vital elements of ignorance and surprise in long term decision making over technology choice. Brooks notes that this type of approach in mainstream economics amounts effectively to the adoption of a "zero order approximation", under which the effects of different types of surprise are assumed to tend to cancel each other out [192]. Under conditions of long term equilibrium, such approximations might be held to be reasonable. However, one of the implications of recognising technological momentum and increasing returns, is that, while many will remain inconsequential, certain ostensibly random minor 'surprises' may turn out to exert an overwhelming influence on the later development of a system as a whole. The non-linear dynamic properties of the sociotechnical system are such that the question of precisely which surprises will turn out to be significant, is inherently indeterminate [193]. The 'zero order approximation' at the heart of the orthodox probabilistic treatment of incertitude as if it were mere risk thus breaks down irretrievably. Emerging understandings of the nature of sociotechnical systems thereby reinforce the arguments already reviewed in the last section for the adoption of an alternative heuristic for responding to strict uncertainty and ignorance. Diversity presents one possible candidate for such a heuristic.

A second conclusion relates to the more direct benefits of diversity in the face of technological lock-in and momentum. If the economy itself displays properties which blindly foster concentration, even under conditions where this is not

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[192] Brooks, 1986.

[193] The general properties of nonlinear dynamic systems are the subject of enormous and growing interest (cf books by: Waddington, 1977; Prigogine, 1980; Jantsch, 1980; Prigogine and Stengers, 1984; Gleick, 1987; Stewart, 1989; Stein, 1989; Casti and Karlqvist, 1990; Ruelle, 1991; Waldrop, 1992; Kauffman, 1993; Lewin, 1993; Murray Gell-Mann, 1994; Casti, 1994; Cohen and Stewart, 1994; Johnson, 1995; Coveney and Highfield, 1995 – most of which address the economic implications to some extent). For more detailed discussions of

beneficial to society as a whole, then the importance of considering policies and strategies for deliberate diversification are correspondingly underscored. For instance, in examining the reasons for the economic success of Northern Italy, Grabher and Stark remark that, under one view, "... not systematic coherence but organisational discrepancy is the effective evolutionary anti-body against hegemonic 'best practice solutions'" [194]. They draw a parallel with the quantitative models of Allen and McGlade concerning fisheries, which suggest that the simultaneous pursuit of a diversity of strategies may act to prevent 'lock-in' to unsustainable patterns of exploitation [195]. The message here is that the deliberate pursuit of a diversity of strategies offers a means both to forestall 'lock-in' under increasing returns and to mitigate the 'momentum' acquired by whatever happens to be regarded as 'best practice' under the prevailing dominant paradigm.

Taken together, these arguments should not be seen to imply an often-caricatured 'relativist' position to the effect that 'anything goes' in the social construction or appraisal of technology. Far from it! The empty regions between the channels in Box 3 emphasise the strong deterministic constraints that are imposed by physical, economic and social 'realities'. A position under which *more than one thing* is recognised to be possible is entirely different from one in which it is asserted that *anything* is possible. In fact, given the simple yet robust character of 'increasing returns' models and the extensive empirical literature on the operation of 'sociotechnical systems' reviewed here, the burden of proof might more reasonably be held to lie with the peculiarly expedient position of neoclassical orthodoxy [196]. Why should it be assumed that there will only ever exist a single 'optimal' technological configuration with respect to any particular function or context? What evidence is there that such an idealistic aspiration is ever actually achieved (or even approximated) by real markets? The central insight echoing resoundingly in the literatures of the sociology, history and economics of technology alike is that a more robust and generally applicable prior position is to contemplate the existence of a (limited) number of discrete and conditional local optima [197].

Although only recently underpinned by elaborate mathematical models and detailed empirical historical and sociological work, the straightforward yet profound practical implications of these insights have long been recognised. In warning many years ago of the importance of avoiding dependence on economically inefficient (and even socially and environmentally dangerous) technological '*monocultures*' [198], Brooks offers a prescient and evocative metaphor. If

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the application of these insights to the economics of technology see: Prigogine and Sanglier, 1986; Anderson, Arrow and Pines, 1988; Arthur, 1989b; Arthur, 1993; Ormerod and Campbell, 1993; Ormerod, 1994; Crutchfield, 1994; Allen, 1994; Myers, 1995; Kauffman, 1995.

[194] Grabher and Stark, 1997

[195] Grabher and Stark (1997) on Allen and McGlade (1986). They also draw more exotic (but nevertheless interesting) analogies from the anthropological literature on the deliberate use of randomising factors in indigenous hunting strategies and from population biology, where some degree of 'compartmentalisation' is held to aid the evolutionary preservation of useful character traits (Grabher and Stark, 1997).

[196] Eg: Liebowitz and Margolis, 1995.

[197] On the economics, see, for instance: Prigogine and Sanglier, 1986; Anderson, Arrow and Pines, 1988; Arthur, 1989b; Arthur, 1993; Ormerod and Campbell, 1993; Ormerod, 1994; Crutchfield, 1994; Allen, 1994; Myers, 1995; Kauffman, 1995.. Thompson (1996) makes a similar point in relation to technological risk.

[198] This evocative agricultural analogy was introduced early by Brooks (1973). In elaborating the idea in later work looking at nuclear power and the US car industry in the 1980's, he observes that "[l]ike agricultural monocultures, technological monocultures are highly

decision makers wish to avoid portfolios of policies, technologies or investments becoming locked-in to socially unfavourable monocultures that are vulnerable to catastrophic disturbance or endogenous failure, then they must ensure the maintenance of some level of diversity.

By acting over time to diminish the degree of diversity in a technological market place, then, both lock-in under increasing returns and the acquisition of momentum (or 'autonomy') in sociotechnical systems may be seen as important factors in the inevitable trade-off already discussed between diversity and standardisation. In reality, the position is more complex (and even recursive) in nature. For standardisation is at the same time an important element in the definition and consolidation of sociotechnical systems and in the establishing of challenges to these systems [199]. Realising this, David and Rothwell observe that "[j]ust as the older literature warned of the risk of government regulation leading to the 'standardisation of mistakes', so we must avoid attributing superior normative properties of efficiency to the *de facto* standardisation that may emerge from market competition among technologies under conditions of positive feedback" [200]. Where market institutions engage in monolithic attempts to 'pick winners', they may prove to be no more successful than the much-criticised efforts of would-be state sponsors [201].

A final point that arises from the literature reviewed here concerns the increased transaction costs that (as has already been discussed [202]) are inevitably in many cases a negative consequence of economic diversity. Transaction costs are typically regarded in a pejorative light as being analogous to 'friction' [203]. Yet, recent insights arising in the literature reviewed here suggest that such 'friction' might occasionally be seen to bring certain longer term economic benefits to set against the shorter term inefficencies. One example lies in the forestalling of risks of unmanageable price fluctuations in stock markets, where recent experience with automation has led bodies such as the US Federal Securities and Exchange Commission to conclude that a certain level of transaction cost may exert a beneficial influence [204]. Recognising the radically increased speed of economic transactions in all sectors, Grabher and Stark point out that "… some friction may be essential for the functioning of markets by undermining the positive feedback loops that can lead to lock-in" [205]. Where increased 'friction' is thought a necessary consequence of greater diversity it should not therefore automatically be assumed to be entirely negative in nature. The reality is more complex. As a result, the business of finding a good balance between diversity and the wider performance of technological portfolios is far from straightforward. Whatever position is taken, it does not alter the fact that the phenomena of technological 'lock-in' and 'momentum' and their associated

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successful in a stable and predictable environment (or market). Though more efficient than alternatives, they are less robust when the environment becomes unpredictable" (Brooks, 1986).

[199] David and Rothwell, 1991.

[200] David and Rothwell, 1996.

[201] Cf: Rosenberg, 1996.

[202] In Section 1.1.

[203] Williamson, 1985, 1993.

[204] Grabher and Stark, 1997:542.

[205] Grabher and Stark, 1997.

economic and sociological processes present a third important set of reasons for being more thoughtful and systematic about the role of technological diversity in the economy.

1.4 Accommodating Plural Perspectives

A final rationale for the detailed exploration of the importance of diversity in economics comes from social choice theory. In developing his eponymous ‘impossibility’ more than thirty years ago, Arrow showed in the formal language of set theory that the general derivation of a single social preference ordering (or aggregate social welfare function) over a number of social choice options will violate at least one of a minimal set of five conditions held to be axiomatic by neoclassical economics in the characterisation of individual choice [206]. This seminal work has since been the subject of an entire literature in and of itself [207]. Yet, despite the complexities, the central insight remains intact [208]. In effect, Arrow showed in the most general of terms that it is quite simply ***impossible*** simultaneously to reconcile his rather permissive set of five conditions [209]. In short, it is impossible to aggregate individual preferences in a plural society in a fashion that is at the same time clearly democratic and entirely consistent. No matter how much information is available, and no matter how much consultation and deliberation are involved, no purely analytical procedure can fulfil the role of a democratic political process. In other words, in terms of the theoretical framework underlying neoclassical economics and rational choice theory itself, there can be no single uniquely "rational" way to resolve contradictory perspectives or conflicts of interest in a plural society [210].

The implications of this (and related insights) for the economics of technology, policy and investment choice are clearly profound. The performance of a range of possible technology, policy or investment options is usually characterisable under a number of disparate appraisal criteria. Depending on the context, these may involve consideration of financial, environmental, employment, regional development or other strategic political or economic factors. Even under a relatively narrow commercial perspective, decision-making typically trades-off considerations such as short run profits, long run competitive position, regulatory exposure, reputation management and labour relations. In a public policy context, the range of decision criteria is typically even wider and more disparate. Many individual criteria might themselves be disaggregated into a series of more finely-specified sub-issues. Whether choices are made in a public or a private capacity, the relevant appraisal criteria (and their constituent sub-issues) will often be *incommensurable,* in the sense that they

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[206] Arrow, 1963, 1974.

[207] These issues are discussed in more detail by Kelly (1978), MacKay (1980), (Collingridge, 1982) and Bonner (1986) with a convenient summary of the discussion provided by Pearce and Nash (1981).

[208] Sometimes being labelled “well known” in the critical literature (eg: Rayner and Cantor, 1987; Vatn and Bromley, 1994; Bohmann, 1996). See also: Lele and Norgaard, 1996).

[209] In summary, the conditions are: First, that the ordering of social preferences for each of a set of options should be the same irrespective of the way sub-sets of these options are grouped together (the "free triple condition"). Second, any option that is increasingly favoured by all individuals, should be increasingly favoured in the expression of social preference (termed "non-negative association"). Third, the introduction of new options, or the omission of old ones, should not alter the ordering of preferences for the other options (termed: "independence of irrelevant alternatives"). Fourth, if individuals are able to choose between any two options, then it should be possible to derive a social preference for one of these two options (the "non-imposition" condition). Fifth, under no conditions should social preference be determined by the preferences of any single individual (a "non-dictatorship" condition). It is interesting that a condition imposing equity of weighting to the preferences of all individuals is absent from Arrow's list.

[210] Hogwood and Gunn, 1984. To the extent that they involve the compression of incommensurable values onto a single metric, analytical tools such as the Kaldor-Hicks compensation principle and the Paretian notions of welfare adopted in cost-benefit analysis do not resolve this problem.

cannot readily or unambiguously be aggregated under any single yardstick. It is possible to take different but equally reasonable views on the relative importance of the different decision criteria.

The lessons of Arrow's Impossibility (and, for that matter, of common sense) are thus not just that it is difficult *in practice* to assign overall social priorities to the different considerations which inform technology, policy or investment choice in any given context. Rather, the message is that it is impossible *in principle* even meaningfully to *conceive* of a single 'objective' aggregated ordering of priorities. Such questions are intrinsically a matter of subjective value judgement. Here, as in policy analysis more generally, there can be no straightforward 'analytical fix' for the problems faced in social appraisal. The notion that there must exist a technology, policy or investment choice which is 'optimal' (or even in some sense unequivocally 'best') from the point of view of society as a whole, is fundamentally flawed.

Arrow's Impossibility simply represents in the field of neoclassical economics a problem which is well-known and played out on a daily basis in political debates over technology choice (for instance, in areas such as energy, food, materials, waste management and transport [211]). Despite the obvious difficulties and fundamental contradictions, however, the activity of seeking an 'analytical fix' in the social appraisal of technology and policy remains big business. A wide variety of disciplines and techniques compete for a niche in the market place of methods, including decision and policy analysis [212], life cycle analysis and environmental impact assessment [213], multi-attribute utility theory and multi-criteria evaluation [214], probabilistic, comparative and environmental risk assessment [215], orthodox and 'constructive' technology assessment [216], as well as the various forms of environmental cost-benefit and cost-effectiveness analysis [217]. Although each is distinct in its own way, what many of these approaches hold in common is a tendency to treat the broad notion of investment, technology and policy performance as an objectively determinate quantity, with the task of appraisal being simply to identify the 'best' among a series of options [218]. To this extent, they share the objective of converting the fuzzy and controversial socio-political *problems* of investment appraisal, technology assessment and policy analysis into precisely defined and relatively tractable analytical *puzzles* [219]. Those who are charged with the task of making decisions or developing strategies for technology and policy choice have a strong interest in encouraging these ambitions and upholding their resulting claims. Although the basic difficulties and inconsistencies may be well known to the specialists, they tend to

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[211] Cf: Keeney, Renn and Winterfeldt (1987); Jones, Hope and Hughes (1988) and Hope, Hughes and Jones (1988) for interesting illustrations of the scope of divergent value judgements in the German and UK debates respectively.

[212] Eg: Collingridge, 1982; Winterfeldt and Edwards, 1986; Hogwood and Gunn, 1984.

[213] Eg: Lee, 1989; Wathern, 1988; OECD, 1993; van den Berg, Dutilh, Huppes, 1995.

[214] Eg: Keeney, Raiffa and Meyer, 1976; Janssen, 1994; Nijkamp, Rietveld and Voogd, 1990; Bogetoft and Pruzan, 1991.

[215] Eg: Covello et al, 1985; Suter, 1991; Royal Society, 1992.

[216] Eg: articles in International Journal of Technology Management, 11(5/6), 1996; Rip, Misa and Schot, 1996.

[217] Eg: Pearce and Nash, 1981; OECD, 1989; Pearce and Turner, 1990; Cropper and Oates, 1991.

[218] Although sometimes ambiguous on this point - especially where cultural theory approaches are applied (eg: Schwarz and Thompson, 1990, cf: critique in Stirling, 1998), constructive technology assessment is properly an exception to this generalisation (cf: Rip, Misa and Schot, 1996).

[219] The distinction is that of Thomas Kuhn (1970).

be neglected in the presentation of analysis for policy and investment decision making [220]. Consequently, untenable aspirations to the 'analytical fix' in technology, policy and social choice remain alive and well in political debate, commercial strategies and popular discourse alike.

It has already been argued that, despite their formal inapplicability, probabilistic techniques continue to be employed under strict uncertainty and ignorance largely because of a dearth of competing approaches. Likewise, continued pursuit of the 'analytical fix' in social appraisal more generally seems to owe more to a perception of a lack of viable alternative techniques than to any deeply held faith in synoptic objectivity [221]. Yet it is here that there occurs a rare and quite remarkable bit of serendipity. For just as the strategy of not putting all the eggs in one basket offers a coherent response to strict uncertainty and ignorance, so too might the spreading of resources across a diverse portfolio of technology, investment or policy options offer a basis for a systematic and transparent way to accommodate divergent interests and values [222]. Where it is impossible to identify a single option as optimal (or even unequivocally 'best') under a variety of different perspectives, it may nevertheless prove to be a relatively tractable task to construct a *portfolio* of diverse options in such a way as to accommodate all relevant viewpoints. Of course, as in the consideration of diversity as a means to foster innovation and growth, hedge against ignorance or mitigate lock-in, here too the crucial question concerns the best way to go about characterising diversity and conducting the trade-off between this diversity and the various divergent notions of performance.

In a general sense, the potential role of diversity in this context has not gone entirely unrecognised. For instance, in considering environmental policy issues, James recognises the requirement for techniques to 'manage diversity' in order to maintain and reflect political plurality [223]. Lélé and Norgaard also note the importance of maintaining plurality in the particular task of constructing policies and strategies aimed at achieving sustainability [224]. Similarly, in calling for regional policy to tolerate 'ecologies of social logics', Grabher and Stark also perceive wider social benefits of diversity [225]. Developing Luhmann's concept of the 'social immune system' [226], they identify diversity with a "tolerance for ambiguity" and, as such, with the 'intelligence' of social and economic systems [227]. Seen in this way, the pursuit in parallel of a diversity of investment, technology (and, perhaps, policy) choices confers a kind of 'socio-political resilience' analogous to (but distinct from) the resilience already discussed in the context of decision making under strict uncertainty and ignorance

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[220] Cf: Stirling, 1997.

[221] Collingridge. 1980, 1982.

[222] An illustrative, schematic pilot exercise in this regard may be found in Stirling, 1997.

[223] James, 1990.

[224] Lélé and Norgaard, 1996. Walker, Narodoslawsky and Moser also recognise economic diversity and connectedness as important aspects of sustainability (1996).

[225] Grabher and Stark, 1997.

[226] Luhmann, 1991.

[227] Grabher and Stark, 1997.

[228]. Instead of representing sustained performance under changing circumstances, ‘socio-political resilience’ represents sustained performance under divergent perspectives.

Employing again the metaphor of a multidimensional ‘technological possibility space’ introduced in Box 3, Box 4 below illustrates the way in which what is considered ‘optimal’ under each of a series of different socio-political perspectives can be represented as discrete regions in this space [229]. The point representing each individual technological configuration will lie within certain of these regions and outside others. In these terms, the pursuit of a diverse portfolio of technologies would be represented by a distribution of points in this space. The potential for diversity to permit the accommodation of all relevant perspectives is realised in one way or another by those portfolios which include at least one point lying within each ‘optimal region’ [230]. Whether or not technological diversification is conceived in these terms, however, it is clear that the ambition of establishing deliberate strategies for the fostering of diversity in technology choice is facilitated both by the advent of information and communication technologies [231], and by a general secular trend toward more “segmented” forms in public and commercial administration [232].

It is claimed in some areas of the literature that technological and institutional diversity may serve to promote democratic political culture in the broadest sense [233]. Alternatively, others highlight possible tensions between diversity and accountability [234]. Much will depend on the way that diversity is fostered and managed. As Grabher and Stark comment), it is “…not simply the diversity of organisations, but the organisation of diversity that is relevant.” [235]. Ultimately, however (in addressing pluralism as in addressing innovation, ignorance and lock-in), the essential trade-offs between diversity and performance in technological portfolios will necessarily remain a matter of intrinsically subjective ethical and political value judgement.

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[228] Cf: Stirling, 1997.

[229] Here, each dimension of the space corresponds with an evaluative criterion applied under at least one perspective. The positions occupied by individual technologies in this space are determined by their intrinsic performance characteristics under the different criteria. The distributions of the ‘optimal regions’ are determined by scaling factors representing the subjective priorities adopted under each individual perspective. This metaphor is returned to in more detail in Section 3.1.

[230] The precise distribution of these points, and the degree to which each of the signified technological options is actually represented in the portfolio are crucial questions raised by this metaphor which are addressed in Section 3 of this paper.

[231] Cohendet, Llerena and Sorge, 1992.

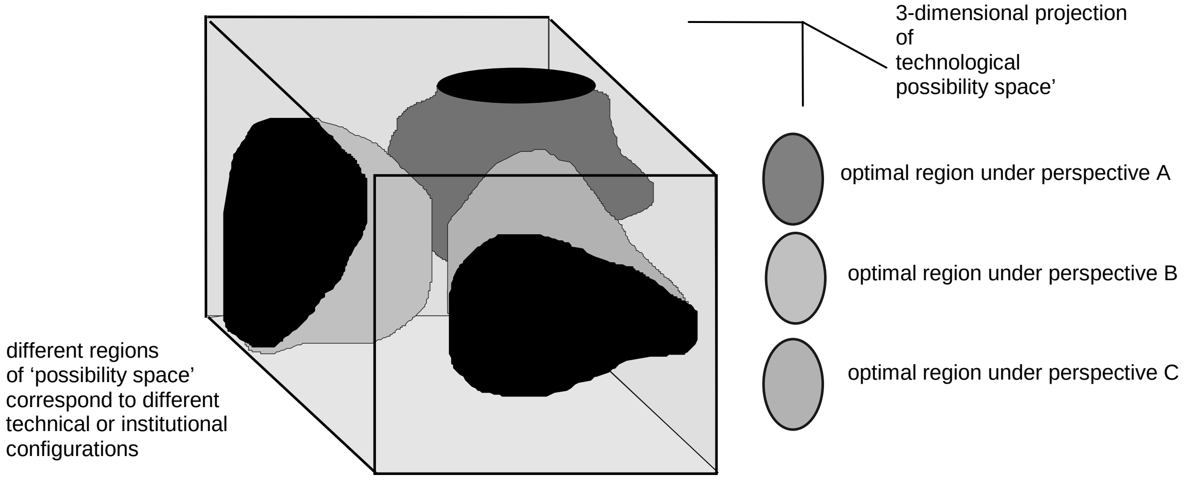
[232] Eg: Mercier and McGowan, 1996.

[233] McGowan, 1989; James, 1990.

[234] Grabher and Stark, 1997. This is especially the case where diversity remains poorly defined and consequently subject to opaque special pleading (Matthews and McGowan, 1992).

[235] Grabher and Stark, 1997.

Box 4: Schematic picture of different ‘regions of optimality’ in technological ‘possibility space’



In recognising this, the imperative for the rigorous characterisation of technological diversity is in no sense weakened. Indeed, the focus falls all the more acutely on the degree to which procedures for the characterisation of diversity are straightforward, systematic, transparent and accessible [236]. The business of arriving at the particular set of value judgements associated with any *actual* trade-off will, of course, not simply be a matter of analysis. In a modern pluralistic society, they will be subject to whatever are the appropriate instruments of democratic political accountability. Yet, even here, political decision making over the social choice of technologies and policies would benefit from greater analytical clarity over the nature and implications of diversity.

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[236] Matthews and McGowan.1992; Mercier and McGowan, 1996.

2. THE CHARACTERISATION OF DIVERSITY

2.1 Some Conventional Views of Diversity

The preceding discussion has established that there exist four broad rationales for an interest in the potential importance of diversity - and especially technological diversity - in the economy. Diversity is variously argued to be (*i*) a key factor in the promotion of beneficial forms of innovation and growth; (*ii*) a means to hedge against exposure to strict uncertainty and ignorance in decision making over alternative technological strategies; (*iii*) a tool for mitigating the adverse effects of institutional 'momentum' and 'lock-in' in long term technological trajectories; and (*iv*) a way of accommodating the disparate array of interests and values typically associated with social choice in modern pluralistic industrial societies. Yet, this entire account has thus far been conducted without addressing one important and obvious question raised at the outset. How exactly are we to define the concept of diversity, such that it is applicable in each of these different contexts?

Economics is not alone in confronting this deceptively simple question. An interest in the concept of diversity is quite highly developed in a wide range of other fields. Although some of the most intense intellectual activity in this area seems to have taken place in mathematical ecology [237], this discipline by no means enjoys a monopoly on relevant insights. This is especially the case, where attention is focused on potential applications of the concept of diversity to the economics of technology, where many of the fundamental properties of the systems under scrutiny are quite distinct from those displayed by ecological systems. For instance, pertinent work on the general characterisation of diversity has also been conducted in disciplines such as conservation biology [238], palaeontology [239], taxonomy [240], pharmacology [241], psychology [242], archaeology [243], artificial intelligence [244], financial management [245] and complexity theory [246] as well as environmental [247], evolutionary [248], and more mainstream [249] economics. Applications of the resulting ideas may be found in a host of further fields, including sociology [250], bibliometrics [251] and information management [252].

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[237] For instance, books by Pielou (1977), Grassle, Patil, Smith and Taillie (1979), especially, the review by Magurran (1988) and numerous articles cited elsewhere in this paper.

[238] Eg: articles in Forey, Humphries and Vane-Wright, 1994.

[239] Eg: Runnegar, 1987; Gould, 1989.

[240] Eg: Sneath and Sokal, 1973 etc.

[241] Eg: Bradshaw, 1996.

[242] Eg: Junge, 1994.

[243] Eg: Leonard and Jones, 1989.

[244] Eg: Cohen, 1985.

[245] Eg: Lumby, 1984.

[246] Eg: Kauffman, 1993

[247] Eg: Swanson, 1994.

[248] Eg: Saviotti, 1996.

[249] Eg: Weitzman, 1992, Solow, Polasky and Broadus, 1993.

[250] Eg: Haughten and Mukerjee, 1995.

[251] Eg: Gomez, Bordons, Fernandez and Mendez, 1996

[252] Eg: Serebnick and Quin, 1995.

Such is the scope for quite fundamental empirically- and theoretically-derived divergences of perspective, that (even within a relatively narrow field such as ecology), some specialists have been led to despair that "diversity does not exist" [253]. Perhaps reflecting this crisis of confidence, it is striking that many quite elaborate discussions of diversity omit to define the concept at all [254]. However, despite the many differences of emphasis, virtually all notions of diversity boil down to pretty much the same thing at the most general of levels. For, no matter where it is found, the concept of diversity relates "to the ***nature or degree of apportionment of a quantity to a set of well defined categories***" [255].

Unfortunately, such apparently straightforward definitions can often give rise to as many questions as they resolve. This general formulation for the designation of the term 'diversity' is no exception. For instance, even allowing for the arbitrary nature of what constitutes a relevant "quantity" under different circumstances, it is possible to distinguish at least three principal subordinate questions.

i) How many categories constitute a "set" – how finely disaggregated should they be?
ii) How are we to characterise the "nature or degree" of apportionment between categories?
iii) What criteria are we to employ in making "well defined" distinctions between categories?

In contemplating the practical implications of these critical questions, there emerge many interesting and potentially instructive differences of emphasis between different disciplinary perspectives on diversity. For instance, it is perhaps surprising, given their close cultural and epistemological links, that there is a clear contrast between conceptions of biodiversity in ecology, conservation and palaeontology [256]. Under ecological perspectives, (where well-established taxonomic schemes – and especially the concept of the 'species' - largely resolve problems of category definition), attention tends to focus almost exclusively on questions of category-counting and apportionment. In evolutionary studies, however (where palaeontological and genetic approaches are seriously limited in their capacity to resolve questions of relative abundance – and thus apportionment), attention tends to be directed more at the problems of defining the categories employed in the analysis of diversity [257]. Likewise, in conservation biology, the magnitude of the problem of global biodiversity loss forces attention to be concentrated on the prioritisation of rare species in terms of the degree to which they preserve unique genetic or phenotypic characteristics [258]. Again, this involves a focus on category definition rather than apportionment. Because of the different emphases in different disciplines, insights generated in one field may

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[253] Peet, 1974.

[254] Laursen, 1996.

[255] Author's emphasis (Leonard and Jones, 1989). A very similar formulation is given in (Junge, 1994). See also: Patil and Taillie, 1982.

[256] Cf: Humphries, Williams and Vane-Wright, 1995.

[257] The evolutionary biologist Eldredge notes that "[t]he two indices of diversity – indeed the very meaning(s) of the word diversity – are different in ecology and systematics. The mechanisms of extinction may lie squarely in the province of ecology, but we measure extinction taxonomically squarely within the realm of systematics" (1992b cited in Cousins, 1994).

[258] Eg: Eldredge, 1992a; Forey, Humphries and Vane-Wright, 1994.

illuminate general aspects of diversity which are neglected in others. In order to derive a robust general characterisation of the concept of diversity, then it therefore seems wise to consult as wide a range of empirical and theoretical discussions as possible.

Despite these pronounced differences of context and emphasis, it is remarkable that, in surveying the broad literature on diversity in all the various disciplines identified above, we may distinguish just three distinct general properties of diversity. Each property relates to one of the three principal questions raised above concerning the number and definition of categories and the pattern of apportionment. These may be taken as elements in the formulation of a strict *monothetic* [259] definition of diversity that should be potentially applicable in all those fields where diversity is of interest. In other words, each of the three properties may be held to constitute a necessary but individually insufficient condition for recognising the presence of the overarching property of diversity as a whole. Collectively, identification of the entire set of properties is sufficient condition for recognition of diversity. A wide range of different terminologies are employed in the different areas of the literature for essentially the same concepts [260]. For present purposes, however, the three subordinate properties of diversity will here be termed ‘variety’, ‘balance’ and ‘disparity’ [261]:

Variety refers to the number of categories into which the quantity in question can be partitioned (for instance: the number of functionally redundant - but morphologically or operationally distinct - technological options sustained in parallel by a market) [262]. As such, variety is a simple positive integer. All else being equal, the greater the variety of a system, the greater the diversity.

Balance refers to the pattern in the apportionment of that quantity across the relevant categories (ie: the ‘market shares’ of each of the technological options) [263]. This might most simply be seen as “something analogous to variance” [264] - a set of positive fractions which sum to unity. For a particular system of given variety, the more equal are the fractions, the more even is the balance, the greater is the diversity.

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[259] The distinction between mono- and polythetic category definitions is developed to a high degree of abstraction in taxonomy (Sokal and Sneath, 1963:13; Sokal and Sneath, 1973:20-22). The essential point is well expressed by Clarke, for whom a monothetic category is “– a group of entities so defined that the possession of a unique set of attributes is both sufficient and necessary for membership” (Clarke, 1978:35). “A polythetic group [on the other hand] is – a group of entities such that each entity possesses a large number of attributes of the group, each attribute is shared by large numbers of entities and no single attribute is both sufficient and necessary to the group membership” (Clarke, 1978:36).

[260] The overarching concept of diversity as defined here is variously referred to in the ecological literature as ‘heterogeneity’ (Peet, 1974; Simpson, 1949; Goodman, 1975) or ‘equitability’ (Auclair and Goff, cited in Magurran, 1988); Cohendet, Llerena and Sorge, 1992. For what it is worth, the definition given for ‘diversity’ in the Shorter Oxford English Dictionary (Onions et al, 1973) is “[t]he condition of being diverse [*cf.* ‘different in character or quality, not of the same kind’]; difference, unlikeness”.

[261] More formal expressions for the concepts of variety, balance and disparity are given later in this paper (Section 3.2).

[262] The concept here termed ‘variety’ is (both in economics and ecology) often simply referred to as ‘diversity’ (cf: Magurran, 1988 for ecology and, for example: Cohendet, Llerena and Sorge, 1992; Drehe and Lay, 1992 for economics). Alternatively, it is sometimes referred to in ecology as ‘richness’ (McIntosh, 1967), ‘species density’ (Hurlbert, 1971) or ‘species number’ (Fisher, Corbet and Williams, 1943). The particular term ‘variety’ is also often used in this special sense in economics (eg: Saviotti, 1996).

[263] The concept here termed ‘balance’ is variously referred to in ecology as ‘evenness’ or ‘equitability’ (after Fisher et al, 1943) and ‘dominance’ or ‘importance’ (eg: Sanders, 1968). The pertinent definitions for the noun ‘balance’ in the Shorter Oxford English Dictionary (Onions et al, 1973) are “[e]quilibrium. General harmony between the parts of anything”.

[264] The phrase is Pielou’s in writing of the property of evenness in ecology (1977).

Disparity refers to the nature and degree to which the categories themselves are different from each other [265]. This relates to the way in which the categories are defined (ie: how do the different technological options vary in terms of whatever are held to be their operational characteristics in any given analysis). It is notions of disparity which determine when a particular type of option is recognised as falling into one category and when it judged to be two As such, disparity is an intrinsically qualitative, subjective and context-dependent aspect of diversity. Notions of disparity will vary, depending on the particular frame of reference which is adopted for any given purpose. Whatever position is taken, however, for two systems of identical variety and balance, the system which is seen to include the more disparate options will be regarded as the more diverse.

The relationships between the properties of variety, balance and disparity are shown schematically in Boxes 5 and 6. Box 5 illustrates the basic concepts by representing the categories of option included in an economic portfolio as symbols, with the relative size of the symbols representing balance and the different shapes and shades of symbol representing disparity. Each of the subordinate properties of diversity may vary independently of each other along the three axes shown.

Box 6 extends the metaphor to show the apportionment of individual members of a set of options into categories. Here, each individual symbol is a particular instance of a technology or product (or other ‘option’). The instances are assigned to categories whose disparities are represented by the differences between the types of symbol. Again, it is clear how variety, balance and disparity may vary independently, each making a necessary but individually insufficient contribution to overall diversity.

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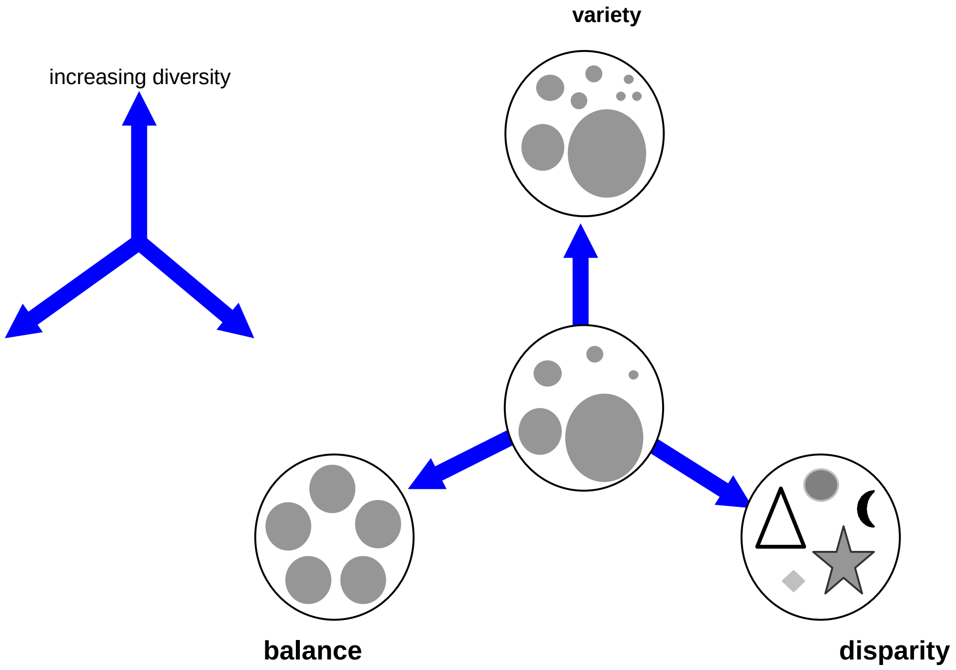
[265] The terminology for this concept of ‘disparity’ is taken from palaeontology (Runnegar, 1987; Gould, 1989). In the economics of biodiversity, essentially the same concept is referred to as ‘diversity’ (Weitzman, 1992; Solow, Polasky and Broadus, 1993). The Shorter Oxford English Dictionary (Onions et al, 1973) yields for ‘disparity, “[t]he quality of being unlike or different”.

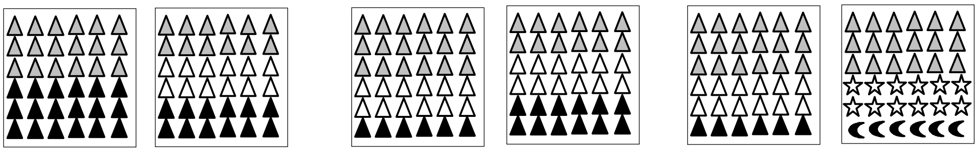
Box 5: The relationships between variety, balance, disparity and diversity



Box 6: The separate contributions to diversity made by variety, balance and disparity

Members of each of the three pairs of portfolios below differ from one another in only one of the subordinate properties of diversity, (marked with a grey ring):

	VARIETY		BALANCE		DISPARITY	
	more diverse	less diverse	more diverse	less diverse	more diverse	less diverse



	VARIETY		BALANCE		DISPARITY	
Variety (number of categories)	**2**	**3**	3	3	3	3
Balance (apportionment to categories)	◭ 50 % ▲ 50 % △ 0 %	◭ 33 % ▲ 33 % △ 33 %	◭ **50 %** ▲ **17 %** △ **33 %**	◭ **33 %** ▲ **33 %** △ **33 %**	◭ 50 % ▲ 17 % △ 33 %	◭ 50 % ☾ 17 % ☆ 33 %
Disparity (differentness of categories)	small	small	small	small	**small**	**large**

In addition to articulating concepts of diversity employed in a wide range of specialist disciplines, this straightforward threefold scheme may also offer the merit of reflecting colloquial understandings of the meaning of the terms 'variety', 'balance', 'disparity' and 'diversity' [266]. After all, when we speak casually of diversity, we are usually referring to some combination of the attributes of difference, number and degree of representation, rather than to any one of these concepts in isolation. Indeed, at a deeper level, it is arguable that each of these concepts is fundamentally and inextricably linked, thus rendering such a scheme a logical necessity [267]. For present purposes, however, the best justifications are pragmatic. The distinctions between variety, balance, disparity and diversity are proposed simply as a useful heuristic for thinking about the general connotations of the term diversity, as a technique for clarifying the inter-disciplinary differences of emphasis discussed above and as a basis for an attempt to construct a more systematic and comprehensive characterisation of economic diversity.

In these terms, then, ecological treatments of diversity tend to focus on balance, and especially variety [268]. Palaeontology and conservation biology, by contrast, concentrate more on disparity [269] while archaeology seems unduly to have neglected the concept of disparity [270]. For its part, much of the economic literature seems to treat the overarching concept of 'diversity' effectively in terms of 'variety' [271]. In certain otherwise sophisticated economic discussions, the term 'diversity' remains essentially undefined [272], whilst in others there is occasionally a degree of confusion between the concepts which are here termed variety and diversity [273]. Elsewhere in the economic literature, rather different conceptions of diversity *are* precisely defined, but remain quite circumscribed in comparison with the threefold definition abstracted here from the diversity literature as a whole [274]. It seems clear that (whether in economics or more generally) approaches to diversity which recognise only the individual sub-properties of variety, balance or disparity are likely to prove intrinsically limited, both in terms of their applicability and their utility in addressing diversity as a whole

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[266] As is noted in the footnotes to the definitions above, each of the terms chosen here reflects common dictionary definitions.

[267] The identification of discrete categories on the basis of their mutual differences is a necessary pre-requisite to any act of enumeration. For, if instances cannot be distinguished, how can they be counted? In this sense, there can be no concept of *variety*, without a concept of *disparity*. Likewise, it is essential that there be an ability to enumerate. Thus, without a concept of *variety*, there can be no concept of *diversity*. Finally there must be some notion of representation (or set membership): to what degree is a given category deemed to be present or absent from the system in question? Without such a concept of *balance* there can also be no concept of *diversity*. The author is grateful for a conversation with Ed Steinmuller on this point.

[268] As exemplified in numerous references cited earlier in this section. In themselves addressing disparity in the context of conservation biology, Williams and Humphries note that biological diversity has historically usually been conceived in terms of variety, sometimes as variety and evenness, and sometimes as variety and rarity (1994). They note the Oxford English Dictionary definition of diversity (cited above) in making the point that, without some reference to a notion of 'differentness' (ie: disparity) , a specialist concept of diversity would be misleading.

[269] Runnegar comments that the study of disparity has tended to arise in macro-evolution, with attention to other aspects of diversity relating more to micro-evolution (1987).

[270] Eg: Leonard and Jones, 1989.

[271] Eg: Metcalfe and Gibbons, 1988; Carlsson and Jacobsson, 1995; Metcalfe, 1992; Kirman, 1992; Cohendet and Llerena, 1995; Llerena and Zuscovitch, 1996; David and Rothwell, 1996. The terminology itself would not be a problem, were it not for the fact that the designation of the term 'variety' is itself often left unspecified (eg: Metcalfe and Gibbons, 1988).

[272] Eg: Grabher and Stark, 1997.

[273] Eg: Cohendet and Llerena, 1995.

[274] Both Weitzman and Solow et al, for instance, advance sophisticated approaches to the economics of biodiversity, but these are effectively based only on the single property here termed disparity (Weitzman, 1992; Solow, Polasky and Broadus, 1993). The particular indices which are proposed in the broad diversity literature are discussed in more detail in Section 2.3.3 of this paper on 'distance metrics'.

One specific example of this can be drawn from the economics of biodiversity conservation. Here, in an otherwise extremely useful contribution that is returned to in detail later in this paper [275], Weitzman proposes a concept of diversity which is effectively limited to addressing disparity alone. The resulting index is entirely insensitive to the number of individuals or the relative abundance of any given species under scrutiny. It fails to distinguish between an ecosystem comprising only a few scattered individuals of the rare species that are of concern, and an ecosystem in which these rare species are represented by relatively large populations. Indeed, a measure of disparity is sensitive only to the mere *existence* of divergent characteristics and not to the *degree* to which they are actually represented. It would not of itself (in an illustrative extreme case) distinguish between the preservation of a single individual of a rare species and the continued thriving of a viable breeding population in a healthy natural habitat. To the extent that Weitzman himself envisages broader application of his diversity concept beyond the field of conservation biology, similar difficulties would emerge [276]. For instance, in an economic context, a restricted notion of diversity-as-disparity would fail to distinguish between a market that is evenly divided between (say) four options and a situation in which a single option dominates 99 per cent of the market, with the other three making up the remaining 1 per cent.

Other apparently comprehensive economic discussions of diversity are circumscribed in a different way. David [277] and Kauffman [278] each advance quite sophisticated models, which (though they differ from each other) also characterise technological diversity essentially in terms of what is here, called variety [279]. In a series of studies of the importance of economic diversity in the context of European integration, Llerena also effectively treats diversity as if it were just variety [280]. In perhaps the most substantive exposition of this view, Saviotti's usage of the concept of 'variety' is likewise defined as "the number of distinguishable actors, activities and objects required to characterise an economic system" [281]. This is clear as far as it goes – and undoubtedly useful for many purposes. However, Saviotti's concept (as David's, Kauffman's and Llerena's) effectively excludes attention to both the 'balance' and 'disparity' properties. In common with the approaches of Weinberg and Solow, such notions of diversity-as-variety fail to distinguish between different distributions of market share (balance). The specification simply that "actors, activities and objects" be "distinguishable" fails to address differences in the *degree* and *fashion* in which they are distinguishable.

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[275] In Section 2.3.3.

[276] Both implicitly in the title and explicitly in the abstract and subsequent narrative (pp.363, 404) Weitzman's article does invoke potential applications of his approach beyond the field of biodiversity conservation (1992).

[277] David and Rothwell, 1991, 1996.

[278] Kauffman, 1993.

[279] Although, in noting that what they call a 'symmetry condition' in the partitioning a market between technologies might be relaxed, David ad Rothwell are effectively implicitly acknowledging the potential importance of what is here termed balance (1996). Likewise, in commenting that the usefulness of his concept of diversity for economics depends on how distinguishable are the states, Silverberg et al are acknowledging the potential importance of what is here termed disparity (Silverberg, Dosi and Orsenigo, 1988).

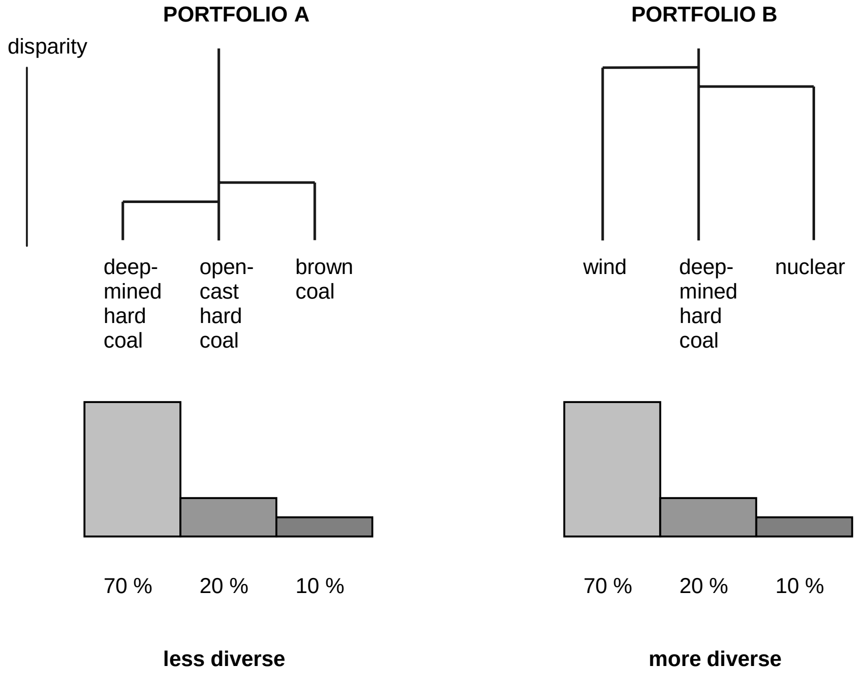
[280] Llerena and Llerena, 1993.

[281] Saviotti and Mani, 1995:372.

To give a concrete example, the result is that such approaches would fail to distinguish between an electricity generating portfolio comprised of deep-mined hard coal, nuclear and wind power technologies and one consisting of the same proportions of deep-mined hard coal, open-cast hard coal and brown coal plant (see Box 7). Differences in technical attributes, operating characteristics and strategic implications (such as those existing between these two groups of options), should constitute an essential aspect of any comprehensive notion of economic diversity. Though it tends effectively to be neglected in much of the literature, disparity remains an essential aspect of economic diversity.

Box 7: The importance of disparity in contemplating technological diversity

Consider two technological portfolios of equal variety and balance, with option disparity represented taxonomically:



Taken together, then, the position might broadly be summarised as follows. Current economic approaches to biodiversity tend to concentrate on *disparity*, while those focusing on general economic and technological diversity tend to be restricted to *variety*. All economic approaches alike tend typically to neglect consideration of the property of *balance* [282]. Despite the importance of the concept of diversity to economics and the large amount of work that has gone on in this area, there seems to remain considerable potential for consolidation, refinement and extension of scope.

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[282] For instance, in stating that “changes in diversity only occur through extinction” Solow, Polasky and Broadus are quite explicitly excluding the concept of balance (1993:61).

2.2 Integrating Variety and Balance

In seeking to characterise economic diversity as a strategic means simultaneously to foster beneficial innovations, hedge against ignorance, mitigate lock-in and accommodate plural perspectives, a rather high level of generalisation is required. Accordingly, variety, balance and disparity have been defined and proposed in the last section as three necessary but individually insufficient subordinate properties of a general overarching concept of diversity. In a brief overview of the biological and economic literature, it has been argued that this framework may be used as a basis for exploring the various approaches taken to diversity in different disciplines and to illuminate any gaps, overlaps or inconsistencies. A more detailed review of further analytical approaches to diversity in all the various disciplines mentioned in the previous section underscores the apparently quite comprehensive scope of this simple threefold characterisation of diversity [283]. For the purposes of the present account, then, it will therefore be taken as axiomatic that, between them, the properties of variety, balance and disparity fully capture the pertinent aspects of the concept of diversity. In this way, it may be argued that the variety/balance/disparity scheme constitutes the basis for a complete general working definition of diversity for the purposes of economic analysis [284].

If this is accepted, then the question becomes one of how we might best go about integrating these three components of diversity into a systematic, transparent and coherent general concept of diversity for application to technological and other economic systems? Beyond this – and more positively – it may even be worth asking whether there is a way in which we can usefully capture such a concept in a simple and robust quantitative index?

In examining the prospects for integrated concepts (and associated general indices) of diversity, by far the most important body of work has been conducted in ecology. Unfortunately (for present purposes), much of the characterisation of diversity in ecology is - quite rightly - determined by circumstantial empirical and theoretical factors which are specific to ecology and cannot be assumed to be transferable to other fields of application. For instance, patterns of species abundance in real ecological systems of virtually all kinds are found to display certain common structural features and empirical

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[283] Although other factors are occasionally proposed as aspects of diversity under particular circumstances, none of these are as coherent or as generally applicable, as variety, balance and disparity. One such factor is ‘scale’. Here, for instance, Pielou favours certain indices of ecological diversity on the grounds that they rise with the total number of individuals in a system (1977). However, the discrete individual organism in ecology has no direct analogue in economic or technological systems, where system volumes are incommensurable and tend to be scaled in terms of units of output of arbitrary size. Moreover, matters of scale in economics are well addressed by orthodox concepts which can be articulated separately with diversity. To the extent that notions of scale are addressed in considering option performance, the issue is highlighted in a later section of this paper (Section 3.2). Also in ecology, Myers (1996) adds a series of more complex factors involving trophic structures, successional stages, biomass and productivity and ‘threshold’ and ‘dominant’ species. However, both in ecology and with respect to analogous properties in other systems, such issues might better be seen as properties in their own right than as subordinate attributes of diversity. The only other potentially additional dimensions of diversity known to the author are those identified in theoretical archaeology by Cowgill (1989) who proposes (along with variety, balance and disparity) the concepts of ‘standardisation’ and ‘uniformity of standardisation’ in order to capture the heterogeneity of individual classes of artefact. Such properties might be regarded as aspects of disparity and are returned to later in this paper (Section 3.2).

[284] Of course this is not to say that the concept of diversity will, in itself, capture or address *all* the pertinent dimensions of innovation, ignorance, lock-in and pluralism. It is simply that a systematic conception of diversity may be helpful in this regard. Detailed attention is given to the characterising of network characteristics in Section 3.4.

regularities [285]. Many of the preferred conceptualisations of ecological diversity are thus *parametric*, in the sense that they are based on assumptions concerning the nature of these underlying patterns [286]. The simple threefold variety-balance-disparity concept of diversity, by contrast, is, in itself, relatively *non-parametric* since it does not rely on any structural models of the particular systems under scrutiny.

If the objective is to formulate a robust general concept of diversity, which is not dependent for its plausibility on a single theoretical framework, then a non-parametric approach is obviously an advantage. Likewise, if the individual systems under scrutiny cannot be assumed *a priori* to display particular structures or regularities, then the adoption of an independent general non-parametric characterisation of diversity is also a prudent step. Since there exist (as yet) no firmly established theoretical principles or empirical generalisations relating to economic diversity (in areas such as the apportionment of market or political support for different technologies [287]), there seems at the moment to be little alternative but to adopt a non-parametric concept of diversity in this field. This is even more true when attention includes investments, policies and their associated institutions. Indeed, despite their many differences, it is significant that the formal approaches to diversity in the economic literature cited in this paper all hold in common the property that they are all essentially non-parametric in character [288].

Once attention is restricted to scrutiny of non-parametric approaches to the integration of variety, balance and disparity, then the field is somewhat narrower. As has already been noted, however, the vast bulk of the ecological literature on diversity has historically failed to address (let alone integrate) the complex and fundamentally subjective concept of disparity [289]. The ecological parallels are thus further narrowed, with an illustrative selection displayed in Box 8 [290].

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[285] For instance, that they yield quasi log-linear plots of proportional abundance against species rank (Magurran, 1988).

[286] May argues strongly for a parametric approach in ecology [May, 1975]. Parametric measures of ecological diversity are variously based on 'geometric', 'log series', 'log normal', 'broken stick' and 'truncated negative binomial' species abundance models. Likewise, 'k-dominance' and 'Q-statistic' measures are specific in their application to graphical plots of rank order against proportional abundance (Southwood, 1978; May, 1981; Magurran, 1988).

[287] Although, as observed by May (1981) the lognormal distribution is ubiquitous throughout physical, biological and human systems. For additional discussion of the wider implications of such 'power laws' in the context of non-linear deterministic systems theory and fractal geometry with a bearing on the topic of the present paper, see: Prigogine, 1978; West and Salk, 1986; Allen and McGlade, 1987; Forrester, 1987; West and Goldberger, 1987; Brock, 1990; Bak and Chen, 1991; Kauffman and Johnsen, 1991; Stewart and Cohen, 1994; Sole, Manrubia, Benton and Bak, 1997. The author is grateful to Sylvan Katz for discussions on this issue over the years.

[288] The assumption of ultrametric distances in the approach of Weitzman (1992) is a special case here which is returned to later (section 2.3.3.

[289] For instance, in an otherwise comprehensive and authoritative survey of the analysis of diversity in ecology, Magurran entirely neglects to consider the concept of disparity (1988).

[290] Many of the most widely used non-parametric indices of ecological diversity are, in fact, effectively just measures of variety or balance alone (rather than dual concept diversity). As can be seen from Box 8, falling into this category are (for variety) the Margalef, Menhinnick, 'numerical richness', and 'species density' indices, and (for balance), the Gini, Berger-Parker and 'Shannon evenness' indices. The field is still further constrained if indices are excluded which are designed for treatment of samples rather than systems as a whole. Important ecological diversity measures falling into this category include the Brillouin and McIntosh functions (see Box 8).

Box 8: Some non-parametric measures of ecological diversity

(after Magurran, 1988; Bobrowsky and Ball, 1989)

Notation	**Ecological Meanings**	**Interpretation for Economic Systems**
A	defined area	defined system parameter
ln	logarithm (usually natural)	logarithm (usually natural)
N	total number of individuals	total system scale
N_i	number of individuals of species i	scale of option i
N_{max}	number of individuals in most populous species	scale of dominant option in portfolio
n	number of individuals in sample	*sampling unlikely to be employed*
n_I	number of individuals of species i in sample	*sampling unlikely to be employed*
p_I	proportion of all individuals in species i	proportional contribution of option I
S	number of species	number of options

Index of	**Index Name** (and source reference)	**Diversity =**
variety	Species Count (eg: MacArthur, 1965)	S
	Numerical Richness (eg: Magurran, 1988)	$\frac{S}{N}$
	Numerical Richness (eg: Odum et al, 1960)	$\frac{S}{\ln N}$
	Margalef (1958)	$\frac{S - 1}{\ln N}$
	Menhinnick (1964)	$\frac{S}{\sqrt{N}}$
	Species Density (eg: Magurran, 1988)	$\frac{S}{A}$
	Species Density (Gleason, 1922)	$\frac{S}{\ln A}$
balance	Berger-Parker (Berger and Parker, 1970)	$\frac{N_{max}}{N}$
	Shannon Evenness (Pielou, 1969)	$\frac{-\sum_i p_i \ln p_i}{\ln S}$
	McIntosh Evenness (Pielou, 1969)	$\frac{N - \sqrt{\sum_i n_i^2}}{N - N\sqrt{S}}$
'dual concept'	Brillouin (Pielou, 1969)	$\frac{\ln N! - \sum_i \ln n_i!}{N}$
	Hurlbert 'rarefaction' (1971)	$\sum_i \left[1 - \frac{\binom{N - N_i}{n}}{\binom{N}{n}} \right]$
	McIntosh (1967)	$\sqrt{\sum_i n_i^2}$
	McIntosh Diversity (Pielou, 1969)	$\frac{N - \sqrt{\sum_i n_i^2}}{N - \sqrt{N}}$
	Shannon-Wiener (Shannon and Weaver, 1962)	$-\sum_i p_i \ln p_i$
	Simpson (1949)	$\sum_i p_i^2$

Before turning to consider insights from that work which *does* seek to address disparity, it will nevertheless be useful to survey the efforts made in ecology to integrate variety and balance alone. Since variety is an integer and balance a set of fractions that sum to one, these are, after all, rather straightforward numerical concepts. In psychology, this more restricted twofold characterisation of diversity has been given the useful label of 'dual concept diversity' by Junge [291], because it addresses together the duality of concepts here termed variety and balance. To many authorities in ecology, dual concept diversity is synonymous with diversity itself [292]. In situations where one system simultaneously displays both greater variety *and* more even balance compared with another system, then it may confidently be held (after Patil and Taillie [293]) to be *intrinsically* more diverse in this restricted ('dual concept') sense [294].

Where a system displays simultaneously greater variety and balance, there is little need for a single integrated concept to recognise that it is intrinsically more (dual concept [295]) diverse. However, it is much more likely to be the case that no single system can be considered unequivocally to be intrinsically more diverse than others in this sense. In such cases, the crucial questions concern the relative importance assigned to variety and balance in arriving at the overall notion of diversity. The position is illustrated schematically in Box 9, in which the relative prominence of different options in an economic portfolio is represented in a pie chart. Where variety is held to be the most important property, System C might reasonably be held to be most (dual concept) diverse. Where a greater priority is attached to the evenness in the balance between options, System A might be ranked highest. In addition, there are a multitude of possible intermediate possibilities, such as System B. The dilemma is clear. Any integration of variety and balance into dual concept diversity must necessarily involve the implicit or explicit prioritisation of the subordinate properties [296].

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[291] Junge, 1994.

[292] For instance, to Pielou "[d]iversity, however defined, is a single statistic in which the number of species and evenness are confounded" (Pielou, 1977:292).

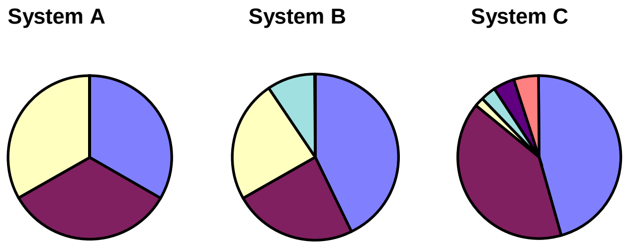
[293] Patil and Taillie, 1979, 1982.

[294] Patil and Taillie hold an ecosystem A to be 'intrinsically' more diverse than a system B if they are alike in all respects except either: (*i*) a new species is introduced in A to share the abundance of one of the species already represented in B; or (*ii*) abundances are transferred between two species in A such as to make them more evenly balanced than in B. This yields an ordering which is identical to that obtained under the application of Solomon's (1975) statistical concept of 'majorisation'. This is analogous to a situation in which the diversity of two communities may be ordered as non-overlapping plots of species proportional abundance against rank (Kempton, 1979).

[295] In other words, assuming both systems to display equal disparity.

[296] It is for this reason, for instance, that May criticises all compound indices of ecological diversity for 'masking' the different properties of richness and evenness (May, 1981b).

Box 9: The question of the relative priority assigned to variety and balance in dual concept diversity



Which system is the more dual concept diverse ?

In an original and seminal piece of work in mathematical ecology, Hill directly addresses this fundamental issue of the trade-off between variety and balance in the measurement of dual concept diversity [297]. Based on the characterisation of diversity in terms of 'proportional abundance', Hill identifies and orders an entire family of possible quantitative measures of dual concept diversity. Each is subject to the same general form:

$$\Delta_a = \Sigma_i (p_i^{a})^{1/(1-a)} \qquad [1]$$

Where Δ_a specifies a particular index of dual concept diversity, p_i represents (in economic terms) the proportional representation of option i in the portfolio under scrutiny and 'a' is a parameter which effectively governs the relative weighting placed on variety and balance. The *greater* the value of the parameter 'a', the *smaller* the relative sensitivity of the resulting index to the presence of lower-contributing options [298]. The family of indices derived by this means is particularly interesting, because it includes among its number two of the most widely used non-parametric measures of 'dual concept' diversity in ecology [299]. Setting a = 1, Hill obtains the famous Shannon-Wiener function (henceforth 'Shannon'):

$$\Delta_1 = - \Sigma_i p_i \ln p_i \qquad [2]$$

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[297] Cf: Hill (1973), Runnegar (1987); also discussed by Kempton, (1979).

[298] In this strict sense, none of the indices in Hill's (1973) family may be seen to be absolutely 'non-parametric', but only relatively so.

[299] A number of other interesting (single or dual concept) diversity indices are also members of Hill's family of 'proportional abundance' measures. Taking extremes where a = - ∞ ; a = ∞ ; and a = 0, respectively, Hill (1973) obtains:

$\Delta_{-\infty} = p_T^{-1}$ (the reciprocal of the proportional representation of the most marginal option)

$\Delta_{\infty} = p_1^{-1}$ (the reciprocal of proportional representation of the dominant option)

$\Delta_0 = \Sigma_i p_i^{0}$ (variety: the simple number of options)

This notorious and enigmatic [300] algorithm has been derived repeatedly from first principles in a number of different disciplines as a robust general means to articulate quantities which are directly analogous to variety (ie: an integer) and balance (ie: a set of fractions which sum to unity) [301]. Accordingly, it is applied (under various names [302]) to uncertainty in statistical mechanics [303], entropy in thermodynamics [304] and complexity theory [305], information in cybernetics [306], concentration in economics [307] and diversity in ecology [308], archaeology [309] and energy policy [310]. The higher the value taken by Shannon, the more (dual concept) diverse is the system.

Setting a = 2, on the other hand, Hill obtains the *reciprocal* of the function variously known in ecology as the Simpson diversity index and in economics as the Herfindahl-Hirschman concentration index (henceforth ‘Simpson’):

$$\Delta_2 = 1 / \Sigma_i p_i^2 \qquad [3]$$

The lower the value taken by Simpson (ie: the higher the value taken by Hill’s Δ_2), the more (dual concept) diverse is the system in question [311].

Perhaps in part due to the spurious authority conferred by its origins in the once-fashionable field of information theory, the Shannon function has become quite well established as a measure of ecological diversity [312]. Despite this (or perhaps, in some cases, *because* of it!), it seems that Simpson is still sometimes preferred to Shannon as a non-parametric index of dual concept diversity in ecology and of concentration in economics. However, when reasons are cited for this preference, they tend often to be either rather ill-founded or somewhat arbitrary.

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[300] In different areas of science, it is variously taken to represent "information capacity" (Resnikoff and Puri, 1986); "incompleteness of knowledge" (Tribus et al, 1974:175); "degree of ignorance" (by Jaynes - Denbigh and Denbigh, 1985:107); and "dispersal" (by Tisza - Denbigh and Denbigh, 1985:104) or "spread" in data (by Guggenheim - Denbigh and Denbigh, 1985:44).

[301] For instance, by Pielou (1969) and Laxton (1978) in relation to ecological diversity and Betts and Turner (1992 – cf: Box 10) in relation to statistical mechanics.

[302] In addition to the various applications noted above, the index itself is the object of much mis-naming, being frequently mis-spelled Shannon-Weiner (eg: Wills, Briggs and Fortey, 1994) or erroneously attributed jointly to a different collaborator of the information theorist Shannon - as ‘Shannon-Weaver’ (Junge, 1994; Peet, 1974; Krebs, 1985) and ‘Shannon and Weaver’ (Bobrowski and Ball, 1989).

[303] Where it is known as "Jaynes' uncertainty measure" (Betts and Turner, 1992).

[304] Where Botzmann introduced it in its continuous form in 1872 (Tribus, 1979) and where it is still employed today (Prigogine and Stengers, 1984).

[305] Where it is referred to under the label of ‘Kolmogorov Entropy’ in some very interesting studies of the relationship between what is here termed dual concept diversity and deterministic chaos in the behaviour of cellular automata in Goodwin, 1994.

[306] Shannon and Weaver, 1962.

[307] Finkels and Friedman, 1967.

[308] Pielou, 1969. A useful recent review is Magurran, 1988.

[309] In Leonard and Jones, 1989.

[310] NERA, 1994; DTI, 1995 after Stirling, 1994, 1995.

[311] Although the opposite is of course true of the reciprocal of Simpson shown in equation 3.

[312] It is unfortunate that this simple algorithm is the subject of so much hype and obscurantism. Its introduction to information theory by Shannon has been enthusiastically described as a development as important as those authored by Newton and Einstein (Tribus, 1979:10) In an illuminating aside, it is reported that von Neumann advised Shannon that he call this function "entropy" because "most people don't know what entropy is, and if you use the term 'entropy' in an argument, you will win every time" (Furstenberg, 1986) May comments that the reason that this (and the related Brillouin) diversity measure are so fashionable in ecology is that they are “linked by an

An example of the former is the curious, unsubstantiated (and apparently mistaken) comment by the economist Stigler to the effect that there exists a precise theoretical rationale for the use of Simpson as an index of concentration, but not for Shannon [313]. In fact, since it is Shannon (rather than Simpson) which is more often derived from first principles to articulate integer and fractional quantities analogous to variety and balance, then quite the opposite might more reasonably be held to be the case [314]. An example of one such formal derivation may be based on the derivation of the Shannon function in statistical mechanics to articulate the twin concepts of 'number of states' (i) and 'probability of realising each individual state' (p_i). These are directly and formally analogous to 'variety' and 'balance'. The rationale is summarised in Box 10.

Beyond this, claims that Simpson is the simpler of the two more prominent 'dual concept' ecological diversity indices rest on an entirely subjective, but nonetheless valid, perception of the relative 'complexity' of logarithmic and exponential functions. However, to those who routinely employ logarithmic functions, it might be perceived with equal validity that Shannon is simpler than is Simpson. Other stated rationales for a preference for Simpson seem simply to reflect a specific instance of (epistemological) increasing returns to adoption, with adherents of Simpson in the social sciences variously citing its greater "familiarity" [315] or (rather lamely) that it is 'recommended by experts" [316].

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ectoplasmic thread to information theory" (1981b:218). The resulting polarisation of discussion is not conducive to the dispassionate critical appraisal of the merits and shortcomings of different possible indices.

[313] Stigler, 1967 (comment on Finkelstein and Friedman, 1967).

[314] Pielou (1969); Laxton (1978); Betts and Turner (1992) cited above.

[315] Haughten and Mukerjee, 1995.

[316] Serebnick and Quin, 1995.

Box 10: Summary of a formal derivation of Shannon as an uncertainty index in statistical mechanics

(after Betts and Turner, 1992:20-25)

Consider a situation of strict uncertainty (cf: Box 2), where:

Ω = number of possible outcomes
U = candidate uncertainty function
C_o, C_1 = constants
p_0 = probability of o^th outcome

In a case where all outcomes (Ω) are equally probable:

Conditions for an effective uncertainty function:
if $\Omega = 1$, $U(\Omega) = 0$ [1]
if $\Omega_1 > \Omega_2$, $U(\Omega)_1 > U(\Omega)_2$ [2]
if $\Omega = \Omega_1.\Omega_2$, $U(\Omega) = U(\Omega)_1 + U(\Omega)_2$ [3]

Consider [3]: $U(xy) = U(x) + U(y)$ [4]

Differentiate [4] with respect to x: $\frac{\partial U(xy).y}{\partial(xy)} = \frac{\partial U(x)}{\partial x}$ [5]

Differentiate [4] with respect to y: $\frac{\partial U(xy).x}{\partial(xy)} = \frac{\partial U(y)}{\partial y}$ [6]

From [5] and [6]: $xy\frac{\partial U(xy)}{\partial(xy)} = x\frac{\partial U(x)}{\partial x} = xy\frac{\partial U(y)}{\partial y}$ [7]

Therefore: $x\frac{\partial U(x)}{\partial x} = y\frac{\partial U(y)}{\partial y} = C_0$ [8]

Integating [8]: $U(x) = C_0 . \ln x + C_1$ [9]

To satisfy condition [1]: $C_1 = 0$ [10]

Set $C_0 = 1$: $U(\Omega) = \ln \Omega$ [11]

In a case where all outcomes (Ω) are of unequal probability:

In a long series of trials ($N \to \infty$), though probabilities (p_o) differ, all *sequences* of outcomes (Np_o) will be equally probable.

Uncertainty over the *sequence* of Ω in N trials, $U_N = \ln \Omega = \ln \frac{N!}{\prod_o (Np_o)!}$ [12]

To satisfy condition [3]: $U_N = N.U$ [13]

From [12] and [13]: $U = \frac{1}{N} \ln \frac{N!}{\prod_o (Np_o)!}$ [14]

Using Stirling's approximation for large N: $\ln N! = N.\ln N - N$ [15]

From [14] and [15], it follows that: $U = -\sum_O p_O \ln p_O$ [16]

Interpretation in terms of 'dual concept' economic portfolio diversity:

If Ω is taken to represent '*the number options contributing to a portfolio*' (variety). The '*probability of o^th outcome*' (p_o) is then directly analogous to the '*proportional contribution of the o^th option to the portfolio*'. The '*sequence of outcomes*' is equivalent to '*the ordering of option contributions to portfolio output as a whole*'. The result obtained for U may therefore be seen to be formally analogous to that for a measure of 'dual concept' portfolio diversity.

In fact, in addition to being less readily derived from first principles, it may also be that Simpson displays two quite adverse relevant properties when compared with Shannon. The first rests in the sensitivity of the final ordering of systems to changes in the one parameter which is embodied in each index [317]: the base of the logarithms used in Shannon and the exponential power employed in Simpson. Although the actual numerical values taken by Shannon will vary with changes in logarithm base, the rank orderings of different systems will remain constant [318]. In contrast to this, changes of exponent in Simpson may lead to radically different rank orderings for different systems [319]. Since there seems to be no more compelling rationale for the choice of a Simpson exponent of 2 rather than, say, 3, 6 or 12, this seems to be quite a serious practical drawback in the robustness of any individual Simpson-style index as a measure of dual concept diversity [320]. In other words, different Simpson exponents lead to different relative sensitivities to variety and balance, different Shannon logarithm bases do not. Box 11 provides a simple illustration of this point, by showing how changes of logarithm base under Shannon-variants and changes of exponents under Simpson-variants affect the rank ordering of an arbitrary set of ten systems [321].

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[317] The status of Shannon and Simpson as 'non-parametric' measures in ecology relates to the absence of empirically-derived parameters, rather than parameters *per se*.

[318] In other words, Shannon index values are monotonic under changes of logarithm base.

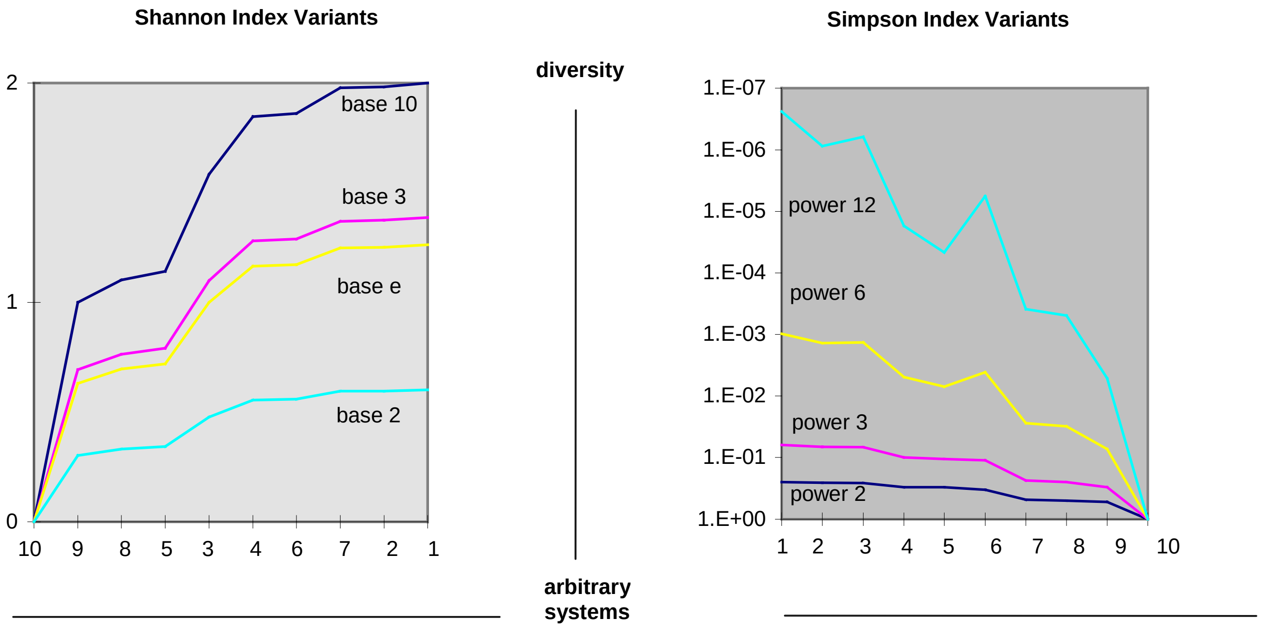
[319] Simpson exponents >2 are obtained by setting parameter values ($2/3 < a < 1$) in Hill's (1973) generic expression [Equation 1]. The reciprocals of these functions are obtained by setting parameter values ($1 < a < 2$).

[320] This is quite graphically illustrated by considering a common interpretation of Simpson to the effect that it represents the probability of two similar options being selected in succession when a system is sampled randomly. If the metaphor is altered to postulate three, four or some other number of successive samples, the rank orderings of different systems may vary.

[321] Although constructed arbitrarily, the ten numbered four-component systems referred to in Box 11 are identical in each graph and have the following compositions:

system:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
option A	0.25	0.33	0.31	0.21	0.18	0.1	0.49	0.5	0.64	1
option B	0.25	0.33	0.24	0.13	0.28	0.2	0.49	0.5	0.32	0
option C	0.25	0.33	0.20	0.44	0.28	0.3	0.01	0	0.04	0
option D	0.25	0	0.25	0.22	0.26	0.4	0.01	0	0	0

Box 11: Changes in rank-orderings under parametric variants of Shannon and Simpson indices



parameter change preserves ranking order

parameter change alters ranking order

The second possible disadvantage of Simpson compared to Shannon resides in a seemingly rather technical point, but one which is potentially significant in any effort to include some consideration of disparity. In her own derivation of Shannon from first principles, the mathematical ecologist Pielou emphasises the condition included as [3] in Box 10 [322]. This concerns the relationships between the index values obtained when a single system is defined using different taxonomies of options. In these terms, this condition requires that the value taken by a diversity index for a system of options which have been disaggregated according to a combined taxonomy should be equal to the sum of the index values obtained for the same system classified under each taxonomy individually [323]. Shannon satisfies this condition, Simpson does not [324]. In other words, if the analysis of diversity is to take account of the disparity of different options through use of formal taxonomies, then Shannon offers a more robust basis for measuring 'dual concept' diversity than does Simpson [325]. This issue is returned to later in this paper [326].

Despite the intense attention that has been devoted to this problem over the years, there is a sense in which the voluminous literature on the quantification of dual concept diversity represents little more than "a group of measures in search of application" [327]. As with efforts to quantify and aggregate any complex, multidimensional property, attempts to capture the full character of dual concept diversity must always remain an intrinsically subjective and context-dependent activity [328]. Accordingly, aspirations (still more,

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[322] Pielou's conditions are (for a set of S options with proportional representation p_i) as follows. First, that a diversity function f(S) should take a maximum value when $p_i = 1/S$ for all i. Second, that f(S) should remain unchanged if we postulate an (S+1)th or (S+2)th class of options with zero members. Third, that if we postulate an additional set of classes, then f(S)a + f(S)b = f(S)ab [Pielou, 1977]. The potential applications of this property are discussed in Section 2.3.2 on formal taxonomies.

[323] Ie: the diversity of a system in which options are disaggregated as 'large', 'small' and 'medium' and the diversity of that same system in which options are disaggregated instead as 'red', 'yellow' and 'blue', when summed together, should equal the diversity of the same system under a taxonomy of options distinguishing 'large', 'medium' and 'small' within each of the colour categories.

[324] As Peet puts it, only Shannon displays the property of additivity over successive taxonomic dimensions [Peet, 1974]. This point is noted, for instance, by Krebs (1985) and discussed further by Faith (1994).

[325] By employing Simpson in an exercise involving summation over subsystems David and Rothwell (for instance) seem to be willing to set aside this finding (1991).

[326] In Section 2.3.3.

[327] This comment is made in the particular case of archaeological approaches to diversity (Dunnell, 1989). In the field of biodiversity measurement, Williams and Humphries (1994) lament that diversity is a 'pseudocognate' concept, in that users simply *assume* that everybody adopts the same intuitive definition. The question raised is 'what happens when intuitions about diversity differ?'. This is at least as much a problem in economics as it is in archaeology or biology.

[328] It is for such reasons that Heywood (1994) calls for greater pluralism in the measurement of biodiversity and Norton – noting that "[d]iversity measures are "only as 'objective' and as 'descriptive' of nature as are the various boundaries and partitions that have been introduced" advocates an explicitly 'subjectivist' ('hierarchical') approach to ecological diversity (1994:26). In Norton's terms, it is not that there is *no* correct description of reality but that there are *too*

claims) to derive uniquely compelling, definitive or 'objectively' complete indices often amount, at best, to little more than numerology [329] and, at worst, to what Berlinski denounces as the "deplorable and pernicious … use of mathematical methods for largely ceremonial purposes" [330]. Once locked-in to a particular conception, there may be tendencies to be seduced by the facility of calculation and descend into a blind faith that "[d]iversity is what the diversity index measures" [331]. Indeed, it may sometimes be too easy to forget the essential distinction between the measurement of some particular concept of diversity, and establishing the *meaning* and *value* of this property in any given context [332]. The point cannot be made strongly enough that judgements over what is the most appropriate index of dual concept diversity may quite reasonably vary from case to case.

On the other hand, there is the problem that "if you can't measure it, you can't manage it!" [333]. Given the potential importance of diversity as a strategic means to foster innovation and growth, hedge ignorance, mitigate lock-in and accommodate plural perspectives, it would be a shame indeed if understanding and implementation of an otherwise positive strategy were inhibited simply by a dearth of clear conventions concerning it's systematic characterisation. In this respect, the currently quite circumscribed, ambiguous and inconsistent nature of much economic discussion of diversity (as documented in the last section of this paper) may present a real problem. The persistence of a sometimes confused or unduly permissive attitude to the characterisation of diversity may in some fields be seen to have fostered the use of a multitude of incommensurable, idiosyncratic and essentially arbitrary diversity concepts [334].

While it is true that any choice among Hill's family of non-parametric dual concept diversity indices will depend on subjective judgements concerning extraneous factors (such as the preferred relative weighting to

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many. These points are well taken by the present author, who has discussed in detail some of the profound theoretical and methodological difficulties associated with attempts to assert hegemonic quantitative aggregating approaches in the field of environmental appraisal (Stirling, 1992, 1997, 1998a, 1998b).

[329] Rindos, 1989.

[330] Berlinsky, 1976 cited in Rindos, 1989.

[331] Reid in Bobrowski and Ball, 1989.

[332] A confusion arguably occasionally displayed by Weitzman, 1992:363.

[333] An alternative form of this business platitude is due to Holdren, who pointed out the confusion that often takes place between "things that are countable and things that count" (1982).

[334] This is arguably the case, for instance in some sociological usage, such as the measurement of diversity in ethnic communities by Hero and Tolbert (1996).

place on variety or balance [335]), this need not be taken to imply that "anything goes!" [336]. In any given context, it *is* possible to draw some pertinent conclusions over the implications of different choices. In particular, it seems clear that, where the objective is to arrive at results which are robust to doubts over parameter values and where there may be a desire to take account of formal taxonomies of disparity, it may often be the case that ***there are good reasons to prefer the Shannon function as a robust general 'non-parametric' measure of dual concept diversity***.

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[335] The varying 'discriminant abilities' of different indices of Hill's (1973) family are explored by Kempton (1979), who favours Shannon in the ecological context. In this regard, Peet (1974) distinguishes two broad types of dual concept ecological diversity indices, 'Type I' which are most sensitive to changes in rare species, and Type II which are most sensitive to changes in abundant species. In these terms, Shannon is most sensitive to changes in proportional abundance of the order of 1/e.

[336] Feyerabend's (1975) provocative slogan is well-justified as a challenge to spurious hegemonic authority of the kind that diversity itself offers a means to avoid. It is ironic that the conceptual confusion caused by a pluralistic 'anything goes' philosophy in the *measurement* of diversity may foster a neglect of the *actual* benefits of pluralism which would otherwise be highlighted by the application of a robust and consensual diversity index!

2.3 Addressing Disparity

So much for variety and balance. What of disparity? In many respects, this concept lies at the very heart of diversity. For instance, it is obvious that (in a locally topical example from Norway) "[a] person who limits his choice of food to ten different kinds of fish is less diverse in his taste than he who selects ten items widely among fish, meat, vegetables and fruit" [337]. Without getting to grips with this crucial aspect, it can hardly be claimed that diversity has been addressed at all. Yet, for all this, the concept of disparity has tended historically to be quite seriously neglected in the various disciplines concerned with the analysis of diversity. As has already been discussed, ecology [338], palaeontology [339], archaeology [340] and evolutionary economics [341] may each in different ways be seen to display tendencies of this type.

Against this background there does seem over recent years to have been a quite marked intensification of efforts in several areas to characterise the particular concept of disparity. In palaeontology, proposed reinterpretations of pre-Cambrian fossil assemblages have provoked a vigorous and quite fundamental debate over the nature of biological evolution [342]. This centres on varying conceptions of the structural forms of living organisms and so has led to widespread recognition of the need to be more systematic in thinking about biological disparity [343]. Meanwhile in ecology a parallel impetus has been provided by increasing recognition of the seriousness of global biodiversity loss and by the advent of national and international legal instruments for reducing the rate of destruction [344]. Practical conservation strategies often involve the prioritisation of different possible targets. These, in turn, require judgements over the "taxonomic distinctiveness" of different organisms. This has again led to pressures for the systematic characterisation of biological disparity [345].

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[337] Junge, 1994:22.

[338] As is noted, for instance, in a seminal article by May (1990) and as evident in the otherwise admirably comprehensive account by Magurran (1988).

[339] As noted by Runnegar (1987).

[340] As is evident in Leonard and Jones (1989).

[341] As is evident in Saviotti (1996) and other references cited in section 2.1 of this paper.

[342] Jaanusson, 1981; Schubert, 1985; Runnegar, 1987; Gould, 1991; Templeton, 1994; Wills, Briggs and Fortey, 1994.

[343] Such as Goulds' notion of 'deep architecture' (1991).

[344] In particular, the 1992 International Biodiversity Convention.

[345] May, 1990.

In facing these demanding analytical challenges, a number of suggestions have been made in different fields as to how the property of disparity might be taken into account along with variety and balance. Although there is a certain divergence over whether the measurement of disparity should be integrated with variety and balance, or simply remain complementary [346], all approaches alike hold in common the essential feature that they involve alternative techniques for the conception and measurement of difference and similarity in a disparate set of system components (such as genera in palaeontology, species in ecology or investment, technology or policy options in economics). For the purposes of exposition, three broad approaches may be distinguished: (*i*) those which refer to statistical concepts such as variance or covariance; (*ii*) those which rely on the establishment of a formal taxonomy or some other scheme for the ordering of options, and; (*iii*) those which involve the direct use of a 'distance metric' of some sort. Each approach will here be considered in turn.

2.3.1 Variance and Covariance

The notion of dispersion in a set of quantified attributes has long been captured at a high level of generalisation in the statistical concept of variance [347]. This basic idea displays obvious parallels with that of disparity as defined in this paper. Both involve notions of similarity and difference. With a central interest in the application of biological models involving selection acting on variation, much discussion of diversity in economics (for instance, by authors such as Metcalfe [348] and Saviotti [349]) has tended to concentrate on the concept of variance. Under such a view, the potential for creative evolutionary change is governed in part by the degree to which different instances of a particular technology or institution differ from each other. If it is assumed that the variation in a given characteristic is random and one dimensional,

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[346] For instance, in a seminal paper calling for the development of a "calculus of diversity" which addresses disparity, May elegantly elides this point. In arguing that "… we need to combine quantitative measures of taxonomic distinctness with more familiar ecological considerations of abundance and geographical distribution", May does not specify whether, by 'combining' he means the development of complementary measures or a single aggregated concept (1990).

[347] Variance is the square of the 'standard deviation' in statistics, given (for a set of N numbers {X_1, X_2, X_3, …, X_N} with mean value m) by: $\sigma^2 = \sum_{i=1}^{N} \left(X_i - m \right)^2 \Big/ N$ where σ is the standard deviation. As such, variance is expressed in units which are the squares of the original units of measurement for the different attributes (eg: Alder and Rossier, 1977).

[348] Metcalfe, 1992.

[349] Saviotti, 1996.

then this potential dynamo for change might satisfactorily be expressed in terms of simple statistical dispersion or variance.

In what would otherwise be one of the most comprehensive discussions of economic diversity, Saviotti describes a quite elaborate version of such an approach [350]. Effectively conflating the concepts of variety and disparity [351], he defines variety in terms of "the number of distinguishable types of actors, activities and outputs required to characterise a system" [352]. This requires the introduction of a crucial distinction between 'variance of characteristics' and 'variety of forms'. In terms of technology, Saviotti's 'variance' refers to the degree of statistical dispersion observed in the values taken by individual characteristics in different instances of a particular type of option. Where there are ***n*** multiple characteristics, he envisages a set of such instances being represented as a dispersion of points in an ***n***-dimensional 'characteristics space' [353].

However, no matter how it is elaborated, the applicability of such a key distinction between 'variance' and 'variety' is undermined unless there is a firm criterion for determining when variance in characteristics may be deemed sufficient to qualify as variety in forms. In other words, serious questions may be begged concerning the 'criterion of distinguishability' which should be applied in any given instance. How are varying *degrees* of distinguishability to be handled? Without attention to such problems, Saviotti's central hypothesis concerning the general tendency in the economy to increasing variety, though interesting and potentially fruitful in its own right, remains insufficiently substantiated and, ultimately effectively untestable. The degree to which variety is perceived to have increased will be a function of the types of distinction made in the definition of the various products and services under consideration.

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[350] Saviotti, 1996.

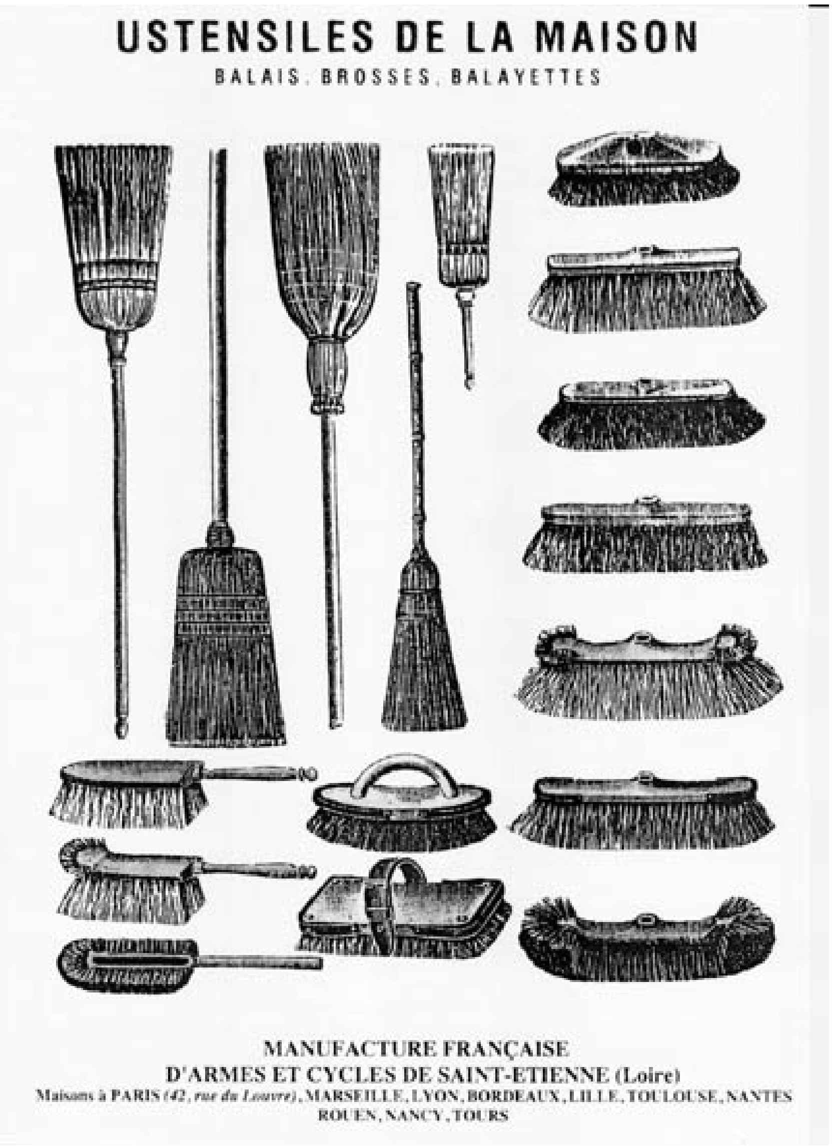
[351] As mentioned earlier in this paper in Section 2.1.

[352] Saviotti, 1996.

[353] Here, Saviotti's approach resembles with respect to the technologies themselves that taken earlier to the systematic characterisation of the services provided by different products by Lancaster (1979), who resolves 'product differentiation curves' in a similar 'characteristics space'. Lancaster addresses the problem of taxonomy by introducing a notion of 'product separability' - essentially making use of the concepts of mono- and polythetic set membership which are noted in Section 2.1 of this paper.

Indeed, a particular instance of this may lie in the problems Saviotti evidently has with the manifestly greater variability of pre-industrial ‘craft products’ compared with industrially mass-produced commodities. At what point do (say) geographically-determined variations in the configuration of a traditional household tool such as a brush become sufficient to amount to a difference in form? The potential ambiguities are well illustrated in Box 12. Which of the items are variations on a particular form and which are distinct artefact types? As the pattern in the statistical dispersions in the attribute values employed in the characterisation of technological disparity become more complex, asymmetrical or multimodal, and as the number of dimensions of variability increase for a given characteristic, then further serious questions arise over the disaggregation and prioritisation of relative importance. The apparent simplicity in the application of the statistical concept of variance to the characterisation of economic disparity (and thence diversity) thus breaks down.

Box 12: ‘Variety’ or ‘variance’ in technological form: the case of traditional household brushes



In short, approaches such as this seem to suffer from something of an occupational hazard in economics and other quantitative fields of study [354], a phenomenon referred to by the economist Daly (borrowing from the philosopher Whitehead [355]) as “the fallacy of misplaced concreteness’ [356]. If it is simply asserted that craft product differentiation is just an example of ‘variance’ rather than ‘variety’ (and thus of no

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[354] Porter, 1995.

[355] Whitehead, 1925 (see also O’Hara, 1997)..

consequence for his hypothesis), then Saviotti's notion of a 'characteristics space' is effectively being reified - treated as if it were a unique and objectively determinable attribute of the system under study rather than a function of subjective and circumstantial features of the analyst's own frame of reference [357]. Under a single circumscribed and tightly-specified frame of reference we may hope to make meaningful statements about disparity in terms of variance. In the general case, however, the greater the attention given to its definition, the more it becomes clear that disparity, like beauty, is ultimately in the eye of the beholder.

The profusion of context-dependent assumptions required of any characterisation of disparity in terms of statistical variance is well illustrated by considering the 'triple concept diversity' proposed by Junge in psychology [358]. This is a compound notion of diversity, seeking definitively to combine the properties here referred to as variety, balance and disparity. Junge derives his measure as the product of his own index of 'dual concept diversity' with Pearson's coefficient of variation between class characteristics [359]. The resulting compound function is displayed in Box 13. As can be seen, it is quite a complicated algorithm. The results obtained are dependent on five different 'proximate factors': (*i*) the number of separate classes of options recognised by the analyst; (*ii*) the proportion of different cases in the classes; (*iii*) the number of types of characteristics recognised by the analyst; (*iv*) the standard deviation in the character values, and; (*v*) the means of the character values. Each of these factors is in turn dependent on a series of conditioning assumptions, such as that concerning the normal distribution of character values implied by the use of the standard deviation. It is clear that the results obtained under such an index will be highly sensitive to relatively minor changes in the values taken by the five 'proximate factors' or their respective conditioning assumptions. In addition, the complexity of the algorithm as a whole invites speculation over the necessity

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[356] Daly, 1989.

[357] This point is acknowledged by Lancaster, whose approach it has already been noted Saviotti's resembles. Paralleling the variance / variety distinction, Lancaster distinguishes (respectively) 'product differentiation' from 'different products'. However, he notes that "[t]he distinction between differentiated products and different products can become somewhat shadowy" (1979:26). Despite this caveat, even Lancaster himself might also be seen to reify a rather simplistic 'monofunctional' notion of a product, by further distinguishing between 'vertical product differentiation' (changes in absolute quantity of all characteristics, ie: quality) and 'horizontal product differentiation' (change in specification, rather than quantity, of characteristic). To take his example, the multiple functions and cultural 'lifestyle' connotations associated with car ownership mean that the difference between a VW and a Mercedes cannot simply be viewed, even in his terms, as 'vertical product differentiation'.

[358] Junge, 1994:22.

[359] Downie and Heath, 1970; Alder and Rossler, 1977.

of the particular form that it takes. Again, relatively minor structural changes of a kind that might reasonably be suggested, might yield radically different results.

Box 13: Junge's use of variance in an index of 'triple concept diversity'

$$\Delta_3 = V_r.\ \Delta_2 = \left(\frac{\sigma}{\mu.\sqrt{n-1}}\right)\left(\frac{1}{\sqrt{s}}\right)\left(\sqrt{s-1}-\sqrt{s\Sigma_i p_i^{\,2}-1}\right)$$

where: Δ_3 = Junge's index of 'triple concept diversity'
Δ_2 = Junge's index of 'double concept diversity'
V_r = Pearson's coefficient of variation between class characteristics $\left(\sigma/\mu.\ \sqrt{n\ -\ 1}\right)$
σ = standard deviation in character values
μ = mean of character values
n = number of characters
s = number of classes
p = proportion of cases in classes

The dangers associated with seductive, but potentially spurious, mathematical authority have already been commented on in discussing the various possible approaches to the measurement of dual concept diversity [360]. Taken together, the host of contingent, context-dependent and even arbitrary features identified here seriously limit the utility of Junge's complex compound 'triple concept' diversity index. For all its uniqueness as an unusually comprehensive measure of diversity, then, Junge's index seems unfortunately to be prohibitively lacking in robustness.

Before turning to alternative approaches to the characterisation of disparity, mention should also be made of another manifestation of the compelling urge to apply the statistical concept of variance to the problem of diversity. Perhaps inspired by the theoretical prominence of portfolio theory in finance management (and within that, of the capital asset pricing model [361]) and under the pressures of time-limited problem-oriented commercial contracts, some consulting firms have sought to apply these off-the-shelf investment management techniques to the general characterisation of energy, agricultural and even biological diversity

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[360] In the penultimate paragraph of Section 2.2.

[361] Cf: Simha, Hemalatha and Balakrishnan, 1979; Lumby, 1984; Brealey and Myers, 1988 and discussion in Section 1.2 of this paper. Although prominent in the academic literature, it is noted there that the techniques of portfolio theory are less well represented in the actual practice of financial stock management (cf: Malkiel, 1989).

[362]. The use of such methods relies largely on the applicability of the notion of *covariance* - the degree to which the characteristics of different options may be held to vary in common under changing circumstances. In these terms, the greater the correlation between the variation of characteristics in different options, the less disparate they may be seen to be.

Unfortunately, such approaches seem to be even more dependent on extraneous and circumstantial assumptions than is Junge's 'triple concept' index [363]. To the extent that they rely on probabilistic conceptions of uncertainty, such approaches are an example of the approach discussed and criticised earlier in this paper [364] - the treatment of the condition of 'ignorance' as if it were mere 'risk'. The results obtained are highly sensitive to the analyst's choice of those outcome scenarios that are worthy of attention and to divergent assumptions concerning the likelihoods of the different outcomes. If diversity is of interest (as has been argued in this paper [365]) partly as a strategic response to ignorance and the potential for 'surprise', then the characterisation of diversity in terms of synoptic aspirations to define 'all relevant scenarios' seems somewhat self-defeating. Scenario-building requires assumptions concerning either the pertinence of past experience, or the credibility of particular expert opinions - neither of which is secure under the conditions of ignorance, 'surprise' and divergent rationality; precisely the circumstances in which diversity is of greatest interest [366]!

Moreover, because attention in scenario analysis is usually confined to certain quantifiable and well-documented performance variables (such as cost), these exercises tend to involve Holdren's confusion "between things that are countable and things that count" [367]. In other words, they tend to neglect those attributes which may be important, but which are not associated with precisely quantified data sets. As with the use of the concept of variance itself, then, a number of further hidden extraneous assumptions are

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[362] Examples are provided by *Environmental Resources Management* (ERM, 1994) on electricity option diversity; *Environmental Resources Limited* (ERL, 1993)] on forestry biodiversity and the *Centre for Social and Economic Research on the Global Environment* (Swanson, Pearce and Cervigni, 1994) on agricultural diversity .

[363] A slightly more detailed critique of the application of such approaches in the Energy Sector may be found in Stirling, 1996.

[364] In Section 1.2 , see especially Box 1.

[365] In Section 1.2.

[366] Cf: Sections 1.2 and 1.4.

[367] Holdren, 1982.

usually required, such as those concerning the form of probability distributions [368]. When these factors are taken together, it seems that notions of covariance from portfolio theory are even less usefully applicable to the general characterisation of disparity than is the concept of variance.

2.3.2 Formal Taxonomies of Disparity

A second general approach to the characterisation of disparity involves a concentration on the classification of options. If the starting point for the analysis of disparity lies in established approaches to dual concept diversity, then the most obvious framework for addressing disparity lies in a focus on the basis for the definition and disaggregation of a set of discrete options. Once this has been done, the argument goes, the problem reduces to an analysis of dual concept diversity amongst this particular set of options. Here, there might be an appeal to two types of authority. On the one hand, analysis might simply make use of some standard convention for the characterisation of the available options. The discrete and mostly well-defined nature of biological species makes this a relatively simple matter in ecology.

In economics, on the other hand, the problem is less straightforward. Economic options (whether technologies or policies) are rarely as distinctive or as discrete as, say, biological species. Nevertheless, certain generalisations may be well established. In energy policy, for instance, there is a tendency to identify the categories ‘coal’, ‘oil’, ‘gas’, ‘nuclear’ and ‘renewables’ as a complete and discrete partitioning of the set of technology and resource options for electricity supply [369]. However, where analysis is more prospective in character, the ‘renewables’ category is often further disaggregated to yield categories such as ‘solar’, ‘wind’, ‘biomass’, ‘waste’, ‘geothermal’, ‘hydro’, ‘wave’, ‘tidal’ and so on. Each of these (and, indeed, ‘coal’, ‘oil’, ‘gas’ and others) may, of course, in turn be further disaggregated.

A particular classificatory scheme (such as any one of these taxonomies of electricity generating resources) may be acceptable under certain restrictive circumstances. But if there is any ambiguity about the basis for

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[368] Indeed, where it is conceded that overlapping probability distributions may be asymmetrical, then there exists no definitive basis for the ranking of options - the same problem that is suffered in purely qualitative scenario-based approaches.

[369] Cf: numerous references in Stirling, 1994.

the definition of the various options, then a serious problem is immediately revealed. Which convention is to be considered the most appropriate in any given situation? The way in which the options are disaggregated will determine the results that are obtained in any analysis of dual concept diversity. For that matter, the same problem applies *a fortiori*, of course, in the analysis of diversity simply in terms of variety alone. Where the basis for the disaggregation of options is open to challenge, any particular set of results will be of correspondingly limited value.

One possible practical remedy to this dilemma lies in adopting a classificatory scheme for the different options which is conservative with respect to the particular hypothesis under test in any given piece of analysis [370]. In a normative analysis, for instance, the disaggregation should be such as deliberately to *understate* the disparity of those options that might otherwise be argued to be favoured in the analysis. To take the example of electricity generating portfolios introduced already, in an analysis which identifies diversity benefits arising from increased contributions from renewable electricity generating options, it should be clear that the disparity of the disfavoured non-renewable options is at least as fully represented in the analysis as is that of the favoured renewables. In this way, conclusions may be drawn from the analysis of dual concept diversity which are relatively robust to divergent conceptions of disparity. However, where the interpretation of analysis is not restricted to the testing of a such a readily expressed hypothesis, such an approach is severely limited.

An alternative form of authority to which appeal may be made in the disaggregation of options lies in the techniques of formal taxonomy. In a field such as evolutionary biology, the well-understood nature of the reproductive processes involved conveniently constrain the overall form that a taxonomy may take [371]. Beyond this, there may exist a relatively robust palaeontological, genetic or cladistic basis for representing disparity as a particular finely-specified taxonomic tree [372]. Indeed, in much recent analysis of biodiversity,

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[370] This is the approach adopted in earlier work by the present author on the topic of energy diversity (Stirling, 1994).

[371] Since (in multi-cellular organisms) speciation events are only ever bifurcations and lineages never rejoin once separated, this effectively determines the structure of the taxonomy as a ‘rooted directed hierarchy’ (Weitzman 1992). However, even here, a variety of different approaches may be taken towards the determination of taxonomies. Williams and Humphries (1994) distinguish phenetic, phylogenetic and taxonomic approaches, themselves preferring the later approach using cladistic classification techniques.

[372] Although there is dispute over which of these disciplines offers the best basis for the derivation of taxonomic relationships, Humphries et al, for instance favour a cladistic approach (Humphries, Williams and Vane-Wright, 1995).

such taxonomies comprise the *entire* basis for the characterisation of biological diversity, without recourse to concepts either of variety or balance [373]. By contrast to this, a more comprehensive approach involving the integration of variety, balance and disparity is alluded to (although largely left unexplored) by a number of mathematical ecologists [374]. Under such a view (and in economic terms), the additional inclusion of disparity in the analysis of dual concept diversity might best be achieved by applying one of the many possible 'cluster analysis' methods to a set of characteristics displayed by the various options from which investment, technology or policy portfolios are constructed.

For instance, the various candidate electricity supply options mentioned above might each be characterised in terms of a range of pertinent attributes such as their commercial, operational and technical features, their environmental effects, their welfare and regional development implications and so on. Using standard 'cluster analysis' procedures (such as those incorporated in many proprietary software packages), such a matrix (perhaps comprising simple binary 'positive' / 'negative' ratings under some criteria) might readily be converted into a taxonomy. This may then be employed as a basic framework for the disaggregation of options, with the analyst simply choosing at what level in the taxonomic structure to make a disaggregation prior to the analysis of dual concept diversity [375].

The difficulty is, of course, that the analysis remains subject to some highly circumstantial determinants. Indeed, the problems of simply adopting a conventional scheme are in some respects compounded. Possible challenges to the validity of a particular well-established taxonomy for the disaggregation of options are replaced by the potential for dispute over the selection of attributes, their relative weighting, the 'scoring' of the different candidate options under these attributes and the choice of the individual clustering algorithms or distance metrics used in the analysis. As is the case with appeals to the authority of some

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[373] Recent examples of disparity-measuring techniques in the field of conservation biology which are fundamentally dependent on the prior availability of a robust and finely-defined taxonomic structure are 'node-counting' techniques (which characterise disparity in terms of discrete taxonomic steps, cf: Humphries, Williams and Vane-Wright, 1995); the 'preservation measure' of Solow et al (which takes account of extinct, as well as extant, forms, cf: Solow, Polasky and Broadus, 1993) and 'phylogenetic moment' techniques (which employ complex optimisation procedures on weighted taxonomies (cf: Horn, Faith and Walker, 1996). Williams and Humphries (1994) show how a variety of taxonomic methods ('root weight', 'higher taxon richness', 'unrooted' and 'rooted' spanning subtree length and 'dispersion') each hold different implications for the assessment of the conservation value of different species.

[374] Peet, 1974; Pielou, 1977.

[375] Such an approach is illustrated in the context of energy diversity in Stirling, 1996.

conventional or conservative disaggregation of options, then, the results obtained under a formal taxonomic approach will only be as robust as the conditioning assumptions.

To some extent, these criticisms might be thought a little harsh. After all, such difficulties are held in common with the application of formal taxonomic techniques in any field. Rightly or wrongly, such concerns do not seem to have unduly inhibited recognition of cluster analysis as a potentially useful tool in other areas concerned with broadly comparable questions of difference and similarity [376]. In contrast to the *ad hoc* character of *a priori* schemes, for any given scheme for the prioritisation of attributes, formal taxonomic techniques at least display the merit of greater transparency in the way that they derive from an explicit set of attributes a unique set of discrete categories of option. Where a taxonomy of disparity is seen to be empirically or theoretically well-established, analysts may feel quite optimistic about its applicability. This might be the case, for instance, in a field such as ecology where the definition and disaggregation of living species is usually relatively uncontroversial.

Elsewhere, however, the circumstances may not be so favourable. In palaeontology, for example, there is often considerable scope for dispute over the nature of the evolutionary relationships between species and lineages [377]. In archaeology, divergent taxonomies often form the centrepiece of theoretical contention [378]. For its part, perhaps wisely, the economics of technology has generally not given great emphasis to systematic taxonomic analysis [379]. The position is even more nebulous with regard to the basis for classification of investment, institutional or policy options. In such cases, the prospects for the robust analysis of economic diversity by combining taxonomic concepts of disparity with dual concept diversity do not look promising.

Such issues may be significant, but they are not decisive. The most serious difficulty in the augmenting of dual concept diversity with a formal taxonomic approach to the disaggregation of options does not lie in doubts over the basis for any given taxonomy. The real problems are more fundamental and less tractable

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[376] Jardine and Simpson, 1971; Sneath and Sokal, 1973; Clifford and Sephenson, 1975; Hand, 1981.

[377] Although they are central to the sometimes-heated debate over the value of cladistic approaches in evolutionary studies (Gould, 1991).

[378] For instance, Cowgill (1989) notes that taxonomic difficulties are far greater in archaeology than in ecology.

than this. For, even if it were possible to derive (for any given purpose) an absolutely authoritative taxonomic scheme and establish definitively at what level on the taxonomy analysis should focus, we would still be faced with a prohibitive limitation. Different terminal nodes in a formal taxonomy will typically vary in their degrees of mutual disparity [380]. Yet, the straightforward application of an index of dual concept diversity will treat each node with equal weight. In other words, a dual concept diversity measure ignores the fact that, for any given level of variety and balance, different patterns in the allocation of specific contributions to individual options may hold different implications for the disparity of the mix as a whole [381]. This problem is illustrated schematically in Box 14.

In Box 14, System A and System B are of equal variety and balance and involve the same options disaggregated under the same taxonomy of disparity. However, though the taxonomy *does* introduce the notion of disparity, it *does not* ensure that the individual identities of the different options are distinguished in the analysis of dual concept diversity on this taxonomy. In fact, *no dual concept diversity measure will discriminate between System A and System B.* Both the Shannon and the Simpson indices would (respectively) take the same value for each of these two systems. Yet, by reference to the taxonomy of disparity shown in Box 14, it should be clear that System B is the more diverse. System B displays a larger contribution from the more disparate option (wind power) [382]. Because it arises from asymmetries in the mutual disparities of the options that have been disaggregated, this might be termed the 'asymmetric disparity problem'.

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[379] Notwithstanding work in the field of 'technometrics' (cf: Grupp, 1994, 1996; Frenkel, et al, 1994). Of course, the lack of a simple lineal 'genetic' mechanism in technology, and the well-known 'Lamarckian' properties of technological evolution, seriously complicate such an undertaking and qualify the results.

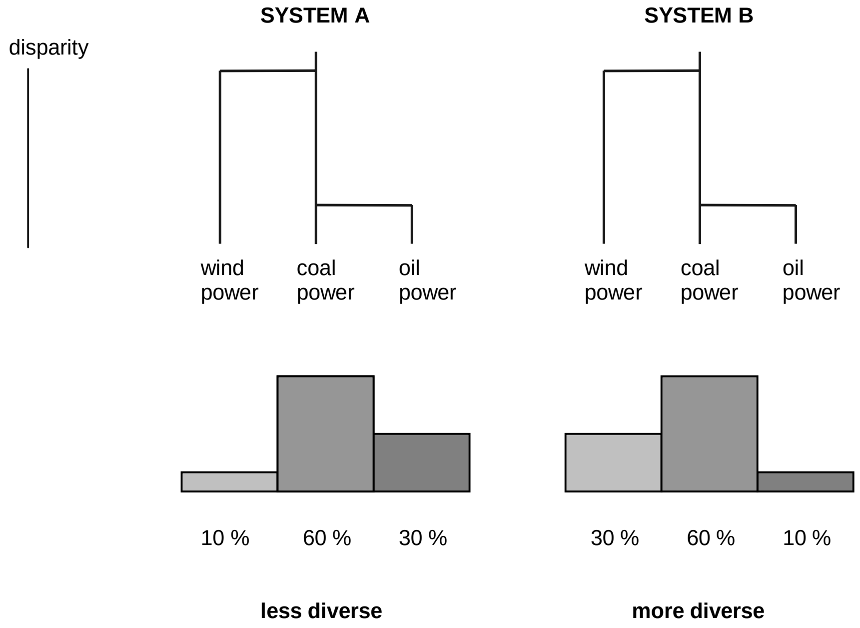
[380] An analogous difficulty is argued by Faith (1994) to affect the 'node counting' approaches themselves. Such techniques cannot distinguish between nodes which have different hierarchical locii in a taxonomic tree. In other words (using Box 14 as a point of reference) , they do not distinguish the relative levels of disparity at which taxonomic branching takes place.

[381] Strictly speaking, this applies only where the taxonomy of disparity is 'asymmetric' in the sense that some options are more disparate from their complements than are others. However, this is likely to be the state of affairs in any practical application to real economic and technological systems.

[382] Another way of looking at this is to imagine that the systems were disaggregated at a higher taxonomic level (above the coal-oil node in the taxonomy). In such a case, the fossil / wind balance in System A would be 95% / 5%, while that in System B would be 80% / 20 %.

Box 14: Applying dual concept diversity to a formal taxonomy: the 'asymmetric disparity problem'

Consider two economic portfolios of equal variety and balance, defined on the same taxonomy of disparity, but with different degrees of disparity between different options:



It follows from the definitions of variety, balance and disparity as the three necessary but individually insufficient conditions for diversity [383], that where variety and balance are equal, the more disparate the system, the greater the diversity. Although addressing certain aspects of disparity, the application of a dual concept diversity index to a formal taxonomy quite simply fails to capture this important feature [384]. The same is true, of course, for any informally-defined conventional scheme. Any approach to the analysis of diversity which is based on the use of a dual concept diversity measure under a formal taxonomic characterisation of disparity will suffer from the asymmetric disparity problem and may therefore be concluded to be quite seriously incomplete [385].

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[383] As set out in Section 3.1.

[384] A similar deficiency is displayed by some taxonomic 'node counting' techniques in the field of biodiversity (eg Forey, Humphries and Vane-Wright, 1994). Where such techniques assign equal weight to within-subtree and cross-subtree groups, they effectively neglect disparity in a similar way (Solow, Polasky and Broadus, 1993).

[385] As such, this factor represents a serious criticism that might be made of earlier work by the present author, but which has only occurred to him since completing this work (Stirling, 1996).

2.3.3 The Direct Use of Distance Metrics

A third (and final) group of approaches to the characterisation of disparity seek to compress this aggregate multidimensional problem down to the fundamental and relatively simple one-dimensional issue of *dissimilarity*. The degree of dissimilarity between two instances of some measurable characteristic is quite readily conceived in terms of the measured difference between the values taken by the characteristic in each instance. In other words, the dissimilarity is characterised as a *distance* on whatever is judged the most appropriate measuring scale. Indeed, to the economist Weitzman, “[d]istance is such an absolutely fundamental concept in the measurement of dissimilarity that it must play an essential role in any meaningful theory of diversity or classification. Therefore, it seems to me that the focus of theoretical discussion must be about whether or not a particular set of distances is appropriate for the measurement of pairwise dissimilarity in a particular context, not about whether such distances exist in the first place” [386].

In some ways, representations of dissimilarity in terms of distances form the basis for both the formal taxonomic and variance analysis techniques already reviewed [387]. The notion of variance applied by Saviotti [388] and employed by Junge [389] implies the concept of an *n*-dimensional ‘characteristics space’, with ‘distances’ being analogous to the dispersion in this space, which in its turn forms the basis for the derivation of character variance [390]. For their part, mathematical approaches to classification of the kind envisaged in diversity analysis by Pielou [391] and Peet [392] use a variety of clustering algorithms and metrics to reduce a set of character-specific distances to a single schematic taxonomy encompassing all options at the same time [393]. Yet, though it may be elegant and graphically appealing, such a reduction has been shown in the last section of this paper to be an incomplete basis for the analysis of disparity. The previous section showed that the problems seem even more pronounced with the proliferation of assumptions required in approaches focusing on variance or covariance. The question then must be, would the same deficiencies arise if the representation of disparity took a step back, and made direct use of the raw

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[386] Weitzman, 1992:365.
[387] In Sections 2.3.1 and 2.3.2 above.
[388] Saviotti and Mani, 1995.
[389] Junge, 1994:22.
[390] Saviotti and Mani, 1995.
[391] Pielou, 1977.
[392] Peet, 1974.
[393] Cf: Jardine and Simpson, 1971; Sneath and Sokal, 1973; Clifford and Sephenson, 1975; Hand, 1981.

information on the dissimilarity of individual characters of the kind on which a taxonomic tree or variance or covariance coefficients are ultimately constructed?

Some years ago, the mathematical ecologist Laxton identified the potential application of dissimilarity metrics as part of a complete compound index of diversity (ie: addressing variety, balance and disparity) akin to that attempted by Junge using variance [394]. Although apparently not himself pursuing the suggestion, he proposed that “gradations of differences and diversity between classes” be addressed along with variety and balance in “compound measures of diversity” by taking account of the “nature of elements” by means of “similarity coefficients” [395]. Although seemingly entirely neglected in the economics of technology, a number techniques have been developed over recent years in the fields of palaeontology [396] and the economics of biodiversity [397] which do make direct use of such ‘similarity coefficients’ in the form of ‘distance metrics’ [398]. For the most part, these techniques have been directed simply at the characterisation of disparity alone, rather than at its integration into a compound measure of diversity such as that alluded to by Laxton and attempted (using the concept of variance) by Junge. However, if successful in capturing disparity alone, such an approach might clearly be of relevance in the wider task of representing diversity as a whole. Accordingly, the following account will review the use of distance metrics as an approach to disparity, before returning to the overall problem of diversity in the next section.

The representation of dissimilarity as a distance metric depends crucially on the nature of the conceptual space within which the distance is to be measured. In palaeontology, this concept has been labelled ‘morphospace’ [399]. It is something akin to Saviotti’s ‘characteristics space’ [400] or the notion of a ‘technological possibility space’ employed earlier in this paper (eg: Boxes 3 and 4). For present purposes, a

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[394] And reviewed here in Section 2.3.1.

[395] Laxton, 1978.

[396] Formal palaeontological definitions for disparity in these terms were introduced by Runnegar (1987) and brought to wider attention by Gould (1989). See also Wills, Briggs and Fortey (1994).

[397] Weitzman, 1992; Solow, Polasky and Broadus, 1993

[398] Eg: Runnegar (1987) or Gould (1989) in palaeontology; Humphries, Williams and Vane-Wright (1995) in ecology and Weitzman (1992) or Solow, Polasky and Broadus (1993) in economics.

[399] Gould, 1991.

[400] Saviotti, 1996. See also Lancaster’s ‘characteristics space’ (1979) and Stankiewicz’s ‘design space’

more precise and general designation for essentially the same concept might be 'disparity-space' [401]. Whatever it is called, efforts to quantify this disparity-space raise a number of serious issues (some of them quite subtle) which are well discussed in the context of evolutionary theory by Gould [402]. What determines the dimensionality and structure of this space? In other words, how many types of characteristic are there perceived to be and what are their inter-relationships and relative importance? What is the 'architectural depth' of the different possible forms [403]?

Such questions are not uniquely invoked by approaches based on the direct use of distance metrics. Indeed, they are inherent in the very notion of disparity and so apply in common under all perspectives. In fact, it is a merit of distance metric approaches that they encourage the explicit consideration of such issues, rather than obscuring them in a multitude of often tacit, sometimes *ad hoc*, prior assumptions such as those introduced by the application of statistical concepts of variance or the formal procedures of taxonomic 'cluster analysis'. Nevertheless, the profusion of possible geometries, dimensionalities and scaling factors on the various possible dimensions of disparity-space *do* present a somewhat daunting obstacle to the identification of a robust general characterisation of disparity.

It is for just such reasons that many, like Norton, have been led to conclude that there can be no overall measure of biodiversity, only a series of different measures for different purposes [404]. In a somewhat despairing comment, the conservation biologist Vane-Wright even remarks at one point that, such are the complexities in the measurement of biological disparity, that the simple number of species (variety) might, after all, present a relatively good proxy for attribute difference [405]! Although they do not field such arguments in their own defence, those analysts of economic diversity (like David [406], Kauffman [407], Llerena [408], Metcalfe [409], Saviotti [410] and Silverberg [411]) who tend to be concerned with the variety component (rather than disparity or balance) might be tempted to take comfort in such comments.

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[401] Alternative terms might be 'criteria space' or 'attribute space'.
[402] Gould, 1991.
[403] Gould, 1991.
[404] Norton, 1994
[405] Humphries, Williams and Vane-Wright, 1995
[406] David and Rothwell, 1991; 1996.
[407] Kauffman, 1993.
[408] Llerena and Llerena, 1993.
[409] Metcalfe, 1992; Metcalfe and Boden, 1992.

Unfortunately, the expedient use of variety as a proxy for disparity is – in economics, at least – more likely than not to be invalid. First, even in principle, such an approach falls foul of the 'asymmetric disparity' problem discussed at the end of the last section: effectively assuming that all identified options are equally mutually disparate [412]. In any case, technological disparity would in several respects be considerably less amenable to such a shortcut than would it's biological counterpart. There exists no parallel in technological evolution for the relatively well-defined and discrete nature of the biological species. The same is even more true for institutions, investments and policy options. Moreover, developmental relationships between species are of a far more tractable lineal nature than are those between technologies. Even were it a serious proposition in the biological sciences, then, the deliberate use of variety as a proxy for disparity seems an entirely untenable proposition for technologies and other economic entities which are not subject to simple lineal relationships.

However, though the problems are undoubtedly formidable, there is no need to succumb to a counsel of despair [413]. Despite the daunting complexities, the successful identification of useful general indices of dual concept diversity does hold out hope that it may prove equally possible to derive robust general measures of disparity and, thence, for overall diversity. What is needed is an insight that narrows down the field of possible approaches to the measurement of disparity, without sacrificing general applicability. Perhaps the most significant recent contribution in this regard (at leas wit respect to economic diversity) lies in the elegant and authoritative mathematical work of Weitzman in the economics of biodiversity [414]. Although his distance metric approach is directed principally at biodiversity, Weitzman clearly also has in mind other

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[410] Saviotti, 1996.

[411] Silverberg, Dosi and Orsenigo (1988) characterise variety as the logarithm to base 2 of the number of options.

[412] Cf: Box 7 and accompanying discussion.

[413] For instance, one candidate for such a possibility may lie in efforts to characterise the *volume* of disparity-space, rather than linear distances. In exploratory work on these lines, Wills uses principal components analysis to characterise disparity in terms of the most important lower-dimensional sub-volumes of disparity-space occupied by a particular system (Wills, Briggs and Fortey, 1994). Although still dependent on the identification and prioritisation of a particular set of operational characteristics, and though remaining sensitive to the form of the distribution of options in disparity-space, such an approach might prove relatively robust to divergent choices of dimensions. Ultimately, however, there remain a host of potentially *ad hoc* details which clutter the choice of volumetric methods. Which are the 'most important' dimensions? Of course, there also remains the problem of how to articulate such approaches with measures of the other attributes of diversity: variety and balance. The fact that the individual options are not an explicit or direct point of reference in a volumetric approach introduces difficulties for the incorporation of variety and balance.

[414] Weitzman, 1992.

potential applications, such as buildings, languages and even technologies [415]. Taken together with the incisive commentary of Solow et al [416], Weitzman's approach will now be considered in some detail.

Weitzman regards his technique as a measure of 'diversity'. However, as indicated by his referring to diversity exclusively in terms of "collective dissimilarity" [417], Weitzman is (in the language of this paper) effectively restricting his attention to disparity alone. For this reason, all his references to 'diversity' will here be substituted with 'disparity'. In the terms of this paper, then, the heuristic motivation for Weitzman's approach is that the disparity of a portfolio of options should be equal to the disparity of that portfolio less one option, summed with the distance between that option and the portfolio as a whole [418]. For this purpose, Weitzman defines the distance between an option and a portfolio in disparity-space as the distance from the outlying option to the nearest option contained within that portfolio. As he readily concedes, such a condition cannot hold in the general case [419]. Instead, what Weitzman does is identify a particular geometric structure for disparity-space under which this condition *does* apply and then derive from first principles using axiomatic set theory a specific index of disparity which *uniquely* displays a number of further properties which he holds to be desirable. His reasoning throughout is governed by a fascinating analogy between a set-theoretic conception of disparity and the mathematical methods of the calculus.

In order to give a flavour of Weitzman's technical achievement, three of his key requirements of a 'nice' disparity index may informally be described in simple terms applicable to the general economics of diversity [420]. One of these is '*monotonicity in options*': if one portfolio is a subset of another, then the disparity of the subset should always be less than that of the encompassing portfolio [421]. Another requirement is a so-called '*twinning property*': the disparity of a portfolio plus an additional option should

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[415] Weitzman explicitly mentions 'artefacts' and specifies that his use of the term 'species' might be taken as a proxy for the general concept of the 'operational taxonomic unit' Weitzman, 1992:363.

[416] Solow, Polasky and Broadus, 1993.

[417] Weitzman, 1993.

[418] Weitzman, 1993.

[419] Weitzman, 1992:367. This point is also discussed in Solow, Polasky and Broadus, 1993.

[420] The three conditions discussed here are those selected as critical by Solow et al (Solow, Polasky and Broadus, 1993).

[421] This formulation is due to Solow et al: $A \cap B$: $\boldsymbol{D}_W(A) < \boldsymbol{D}_W(B)$ (Solow, Polasky and Broadus, 1993). In Weitzman's (1992:376) terms, if a new option (j) is included in a portfolio $\{Q)$, then the disparity ($\boldsymbol{D}_W$) of the resulting portfolio $\{Q \cup j\}$ should be greater than the diversity of the original portfolio $\{Q)$ by an amount which is monotonic with the minimum distance ($\boldsymbol{d}_W$) between the new option (j) and the first portfolio $\{Q)$. Ie: $\boldsymbol{D}_W\{Q \cup j\} \geq \boldsymbol{D}_W\{Q\} + \boldsymbol{d}_{min}\{j,Q\}$, $[\forall Q, \forall j \notin Q]$.

be identical to the disparity of that portfolio taken alone, if (and only if) the distance between that option and the portfolio as a whole is zero [422]. A third condition Weitzman terms a '*continuity*' property, to the effect that the disparity of a portfolio plus an additional option should be a continuous increasing function of the distance between that portfolio and that option [423]. The strength of Weitzman's approach, is that he identifies by such means in a mathematically rigorous fashion a *single* index of disparity which *uniquely* satisfies what in any perspective must seem to be an eminently reasonable minimal set of requirements [424].

The general measure of disparity formally derived by Weitzman in this way is the solution to the recursive dynamic programming function:

$$\boldsymbol{D}_{\mathrm{W}}(S) \;=\; \max_{i \in S}\{\, \boldsymbol{D}_{\mathrm{W}}(S \setminus i) + \mathbf{d}_{\mathrm{W}}(i, S \setminus i) \,\} \qquad [4]$$

Where (in the economic terms of this paper) $\boldsymbol{D}_{\mathrm{W}}(S)$ is the value taken by the disparity of the economic portfolio S, i is an economic option contained in the portfolio S and $\mathbf{d}_{\mathrm{W}}(i, S \setminus i)$ is the distance (in arbitrary units) in disparity-space between the option i and the nearest remaining option in S if i is excluded [425].

There can be little doubt that, in identifying this index, Weitzman makes a considerable contribution to the characterisation of disparity. Unfortunately, when judged in the context of his claims thereby to have developed a "rich theory of diversity" with "ramifications for several disciplines" [426] the utility of his results is more qualified. The first problem is, of course, that Weitzman's index addresses only disparity,

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[422] According to Solow et al: $\boldsymbol{D}_{\mathrm{W}}(\mathrm{A} + \mathrm{j}) = \boldsymbol{D}_{\mathrm{W}}(\mathrm{A})$ **iff** $\boldsymbol{d}_{\mathrm{W}}(\mathrm{j},\mathrm{A}) = 0$ (Solow, Polasky and Broadus, 1993). In Weitzman's (1992:391) more elaborate terms, two options (*i* and *j*) may be considered *identical* if their mutual disparity is zero and if each displays equal disparity with all other options. If there is an option (*k*) which is not included in portfolio $\{S\}$, but which is identical to another option (*j*) which *is* included, then the disparity of the portfolio after option (*k*) has been added $\{S \cup k\}$ should be equal to the disparity of the portfolio from which it is excluded $\{S\}$. Ie: $\boldsymbol{D}_{\mathrm{W}}\{S \cup k\} = \boldsymbol{D}_{\mathrm{W}}\{S\}$, $j \in S$, $k \notin S$, $\boldsymbol{d}_{\mathrm{W}}\{j,k\} = 0$, $\boldsymbol{d}_{\mathrm{W}}\{j,i\} = \boldsymbol{d}_{\mathrm{W}}\{k,i\}$, $\forall i \in S$.

[423] This description is again due to Solow, Polasky and Broadus (1993). Weitzman's own (1992:391) formulation is in terms which are too elaborate conveniently to summarise in a less technical form here.

[424] A number of other requirements are also specified by Weitzman, such as the '*link property*' (1992:378), '*monotonicity in distances*' (1992:392) and (in the terms of this paper) '*maximum disparity that can be added by an option*' (1992:392). The former is a key property relating to the assumption of ultrametric distances, discussed below. Further discussion of the other requirements would add little to the present account.

[425] The solution to equation [4] is unique if it is specified that $\boldsymbol{D}_{\mathrm{W}}(i) \equiv \boldsymbol{d}_0$, $\forall i$ and $\boldsymbol{d}_0$ is normalised by setting it to zero or some large constant (Weitzman, 1992:375).

[426] Weitzman, 1992:363.

rather than diversity as a whole [427]. The implications of this serious limitation have already been discussed in some detail in Section 2.1.

A second difficulty is less obvious, but equally important in its implications for the interdisciplinary applications of Weitzman's approach. This concerns the assumptions about the geometry of disparity-space which Weitzman has to make in order to satisfy his general requirement (discussed above) that the disparity of a portfolio should be equal to the disparity of that portfolio less one option, summed with the distance between that option and the portfolio as a whole. Such a condition is not true of distances in a 'normal' Euclidean space. In fact, it applies only in the case of a rather exotic geometry in which distances are what mathematicians describe as 'ultrametric' [428].

What is interesting about an ultrametric geometry, is that it corresponds to a situation in which any taxonomy derived from the distances in question takes the form of a 'rooted directed tree' [429]. This is a taxonomic structure in which all nodes are branching pairs, with no threefold or higher order branching and, certainly, with no more complex links such as branches which rejoin [430]. As shown in Box 15, this corresponds to a framework under which all relationships between options are, in effect, lineal, with no provision for collateral or contingent causal links. Weitzman refers to his favoured ultrametric structure as a 'perfect taxonomy' and effectively implies, *a priori*, that it is a superior way of ordering any given array of dissimilarity distances [431].

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[427] For their part, Solow, Polasky and Broadus (1993:64) suggest rather incidentally that some account might be taken of variety as well as disparity by raising the inter-option disparity distances ($\mathbf{d}_W$) to some constant power. To be specific, they propose a distance measure $\mathbf{d}'$ such that: $\mathbf{d}'(i,j) = [\mathbf{d}(i,j)]^c$. The lower the value taken by c between 0 and 1, the greater the relative weighting placed on variety at the expense of disparity. However, such a technique would still not take account of the degree of balance in the portfolios under scrutiny and would raise questions over which value would be the most appropriate exponent (different exponents implying different relative weightings on disparity and variety).

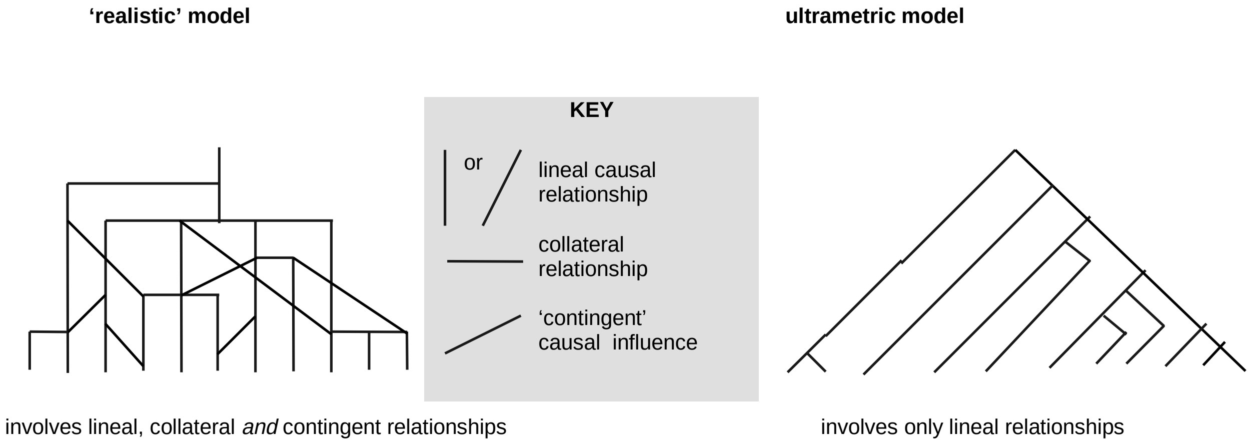
[428] As Weitzman (1992:368) explains by reference to a system S comprising (in economic terms) technologies i, j, k etc, "[p]oints belonging to S have ultrametric distances if for any triple $\{i,j,k\} \in S$: $\mathbf{max}\ \{ \boldsymbol{d}_W(i,j), \boldsymbol{d}_W(j,k), \boldsymbol{d}_W(i,k) \} = \mathbf{mid}\ \boldsymbol{d}_W(i,j), \boldsymbol{d}_W(j,k), \boldsymbol{d}_W(i,k) \}$, …[this] means that for the three possible pairwise distances between any three points, the two greatest distances are equal.". Distances in a Euclidean space, by contrast, obey the less demanding triangle inequality, which requires that (for the same triple) the difference between the two greatest distances is less than or equal to the smallest distance: $0 \leq \mathbf{max}\{\boldsymbol{d}_W(i,j),\boldsymbol{d}_W(j,k),\boldsymbol{d}_W(i,k)\} - \mathbf{mid}\{\boldsymbol{d}_W(i,j),\boldsymbol{d}_W(j,k),\boldsymbol{d}_W(i,k)\} \leq \mathbf{min}\{\boldsymbol{d}_W(i,j),\boldsymbol{d}_W(j,k),\boldsymbol{d}_W(i,k)\}$. Cf: Rammal, Toulouse and Virasoro, 1986; Bradshaw, 1996.

[429] Weitzman, 1992:368. In physics, the unique structural form corresponding to an ultrametric set is referred to as an 'indexed hierarchy' (Rammal, Toulouse and Virasoro, 1986).

[430] Rammal, Toulouse and Virasoro, 1986.

[431] Weitzman, 1992:369.

Box 15: Some implications of an assumption that disparity relationships are ultrametric in form



Weitzman acknowledges that "[i]t is only rarely that distances come in ultrametric form" [432]. Where an actual set of disparity distances are not ultrametric in character (as would be the case, for instance, for most random distributions of points in a Euclidean disparity-space [433]), Weitzman postulates the derivation of a "maximum likelihood branching evolutionary structure" [434] - a bifurcating taxonomy which best approximates the actual array of distances [435]. In this way, Weitzman's choice of a favoured geometric (and associated taxonomic) model is largely expedient, since it is the unique properties of ultrametric distances which allow him to derive an elegant solution to the general problem of disparity as he has formulated it. The question naturally arises as to how robust is the assumption that all disparate systems may usefully be modelled *as if* they resulted from an exclusively bifurcating genealogical-type evolutionary process?

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[432] Weitzman, 1992:375.

[433] Ie: from the definition in note 428 above, all those triplets of points not comprising isosceles triangles.

[434] Weitzman, 1992:384.

[435] This is achieved by means of a 'fundamental representation theorem' (1992:384-390) which Weitzman regards as a "central theme" of his paper (1992:375).

Unfortunately, such an assumption constitutes a highly dubious basis for a general approach to the measurement of disparity. Weitzman himself recognises that exclusively bifurcating taxonomies are not a good general model for all forms of disparity-generating processes [436]. Indeed, even in the field of biological evolution, serious questions have been raised over the universal assumption of branching taxonomies [437]. Since the two greatest distances between any triplet of elements are always the same, an ultrametric geometry incurs a difficulty analogous to the 'asymmetric disparity' problem illustrated for formal taxonomic approaches in Box 14 in the last section. Indeed, as many conservation biologists have pointed out, the adoption of an ultrametric geometry amounts effectively to an assumption that disparity changes at an equal rate on all branches of the taxonomy. In biology, just as in economics, such assumptions cannot easily be justified [438]. Economic and technological disparities are *not* generated on all developmental pathways at a regular 'clock-like pace' [439]. Indeed, from the point of view of the economics of technology (and many other potential fields of application), even the assumption of exclusively bifurcating evolutionary structures would be very difficult to sustain. Technological lineages display important 'collateral' and contingent relationships, as well as Lamarckian and teleological evolutionary qualities [440]. Technological and institutional change are emphatically *not* simple genealogical branching processes.

Beyond these quite profound theoretical difficulties, a third and final problem lies in the complex recursive character of Weitzman's disparity function. This renders the practical business of computation somewhat difficult for systems with many elements. Indeed, Solow et al report Weitzman's measure to be effectively incalculable in the case of an analysis of just 14 species of crane [441]. This is a shame, given that many technological portfolios that are of potential interest in the analysis of economic diversity comprise a greater number of options than this. An example might be the energy policy options mentioned above.

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[436] Weitzman, 1992:375.

[437] Such a model is not even necessarily applicable to prokaryote evolution, still less that of precursor bio-molecules (Maynard-Smith, 1989).

[438] Faith, 1994; Humphries, Williams and Vane-Wright, 1995.

[439] The phrase is that of Humphries, Williams and Vane-Wright (1995).

[440] In this context, the term '*collateral* relationship' is taken to refer to lineal branching of indeterminate order greater than two and the term '*contingent* relationship' is taken to refer to an inter-option influence which is not one of simple lineal descent.

[441] Solow, Polasky and Broadus, 1993.

From the point of view of computational efficiency alone, then, further serious doubts have unfortunately been raised over the efficacy of Weitzman's measure.

Between them, then, the omission of variety and balance, the idiosyncratic distance measure, the restricted applicability and implications of an 'ultrametric' disparity assumption and the computational problems associated with this sort of recursive algorithm constitute serious obstacles to the acceptance of Weitzman's proposed measure as a definitive and comprehensive general index of diversity for use in the economics of technology and other fields. Despite these problems, however, Weitzman's seminal work does hold important lessons for the derivation of a robust general index of disparity, and thence, perhaps, of diversity as a whole. Most importantly, it raises the question of what form of geometry (if any) might most appropriately be attributed to disparity-space, both in the general case and with particular reference to technological and wider economic diversity?

In the final part of this paper, an approach is proposed under which this problem might systematically be addressed. Before turning to these final questions, however, it may be helpful to take a few steps back and look more closely at the analysis of diversity in the general context of appraisal.

3. THE ANALYSIS OF ECONOMIC DIVERSITY

3.1 Option Appraisal and the Geometry of Disparity-Space

It was established in the first part of this paper that there exist four broad rationales for an interest in the potential importance of diversity - and especially technological diversity - in the economy. Diversity is variously argued to be (*i*) a key factor in promoting beneficial technological and institutional innovation; (*ii*) a means to hedge against exposure to strict uncertainty and ignorance in decision making over alternative strategies; (*iii*) a tool for mitigating the adverse effects of institutional 'momentum' and 'lock-in' in long term technological trajectories; and (*iv*) a way of accommodating the disparate array of interests and values typically associated with social choice in modern societies. Conceived in any of these ways, diversity is thus an inextricable factor in the economics of choice among contending technology, policy or investment options. However, instead of being a feature of the performance of *individual* options, economic diversity is an irreducible attribute of the performance of *portfolios* of such options taken as a whole.

The priority that might be assigned to diversity in appraisal will be a reflection of the trade-offs between the various benefits and disbenefits which that diversity is held to confer and the performance of the individual options under other performance appraisal criteria (such as cost) [442]. In other words, the greater the desire to promote innovation, hedge against ignorance, mitigate lock-in or accommodate divergent views, the greater the priority that might be assigned to the achievement of *some degree* of diversity [443].

Each of the various rationales for diversity will be of different importance in different contexts. From the point of view of long term technology strategies, for instance, all the above issues might be expected to play some role in the formulation of public policy. Where decision-making is undertaken by some more circumscribed, but still collective, body (such as the board of a large private corporation or intergovernmental agency), then the hedging of ignorance and, perhaps, the accommodation of divergent views, may be more likely to predominate. Even in situations where choices are made by a single decisive

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[442] The disbenefits, as well as the potential benefits, of economic diversity are also discussed in sections 1.1 to 1.4 of this paper.

individual without reference to wider considerations or the preferences of others, it is likely that there may remain doubts over the degree of ignorance suffered in appraisal and thus a rationale for some degree of diversification. Only if a decision-maker perceives one particular option to be overwhelmingly attractive, feels fully confident in the available performance appraisals, is absolutely certain about a particular scheme of priorities and sees no need to accommodate the viewpoints of others, will she attach *no weighting at all* to diversity.

This question of how to strike an optimal balance between the various benefits and disbenefits of diversity, together with performance under other criteria, will be returned to in the next section. For now, the point is simply that, seen in this normative light, the characterisation of portfolio diversity is an intrinsic aspect of performance appraisal. Different appraisal contexts will involve different particular conceptions of the potential benefits and shortcomings of diversity and thus different trade-offs between diversity and other measures of performance. In situations where no value at all is placed on diversity, then (all else being equal) only that option with the best overall performance would ever be pursued. Only if the contributions of apparently better performing options were constrained, would successively poorer options be turned to in sequence of diminishing performance. In a deliberately diversified portfolio, on the other hand, apparently less attractive options are turned to before the possible contributions of apparently preferable options have been exhausted [444]. The proportional representation of each option in the portfolio will represent a balance between the priority assigned to the various aspects of diversity, the performance of the various options under other appraisal criteria, the priorities that are assigned to these criteria and any constraints that there may be on the contributions which may be made by individual options.

Rather than complicating the task of characterising diversity, conceiving of the problem in the normative terms of appraisal may actually significantly simplify the issue. For all approaches to the appraisal of options (no matter what particular techniques they employ) involve the registering - and, where possible, measurement - of performance under a series of appraisal criteria. Although often implicit, this is as true in

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[443] At higher levels of diversity, of course, the marginal benefits of further increasing diversity might be expected to be negative. The form taken by the ‘cost curve’ for diversity will, of course, be highly subjective and context dependent.

[444] This point is pertinent where options involve the consumption of some limited resource and is elaborated in the next section.

orthodox economic cost-benefit analysis as it is in decision or life cycle analysis, technology assessment or (most explicitly) multi-criteria evaluation [445]. In each case, the business of appraisal will automatically involve the construction of a matrix of those characteristics that are held to be relevant in any given context. The simplification lies in the drawing of a parallel between such performance matrices and the distribution of options in disparity-space. ***Appraisal criteria are analogous to dimensions of disparity.***

As illustrated schematically in Box 16, any array of performance scores and priority weightings for a range of ***z*** options under each of ***n*** appraisal criteria may be represented as a set of ***z*** co-ordinates in an ***n***-dimensional space. The distances between the option co-ordinates in this space are directly analogous to their disparities, in a fashion that is directly operational and pertinent to the particular appraisal under consideration [446].

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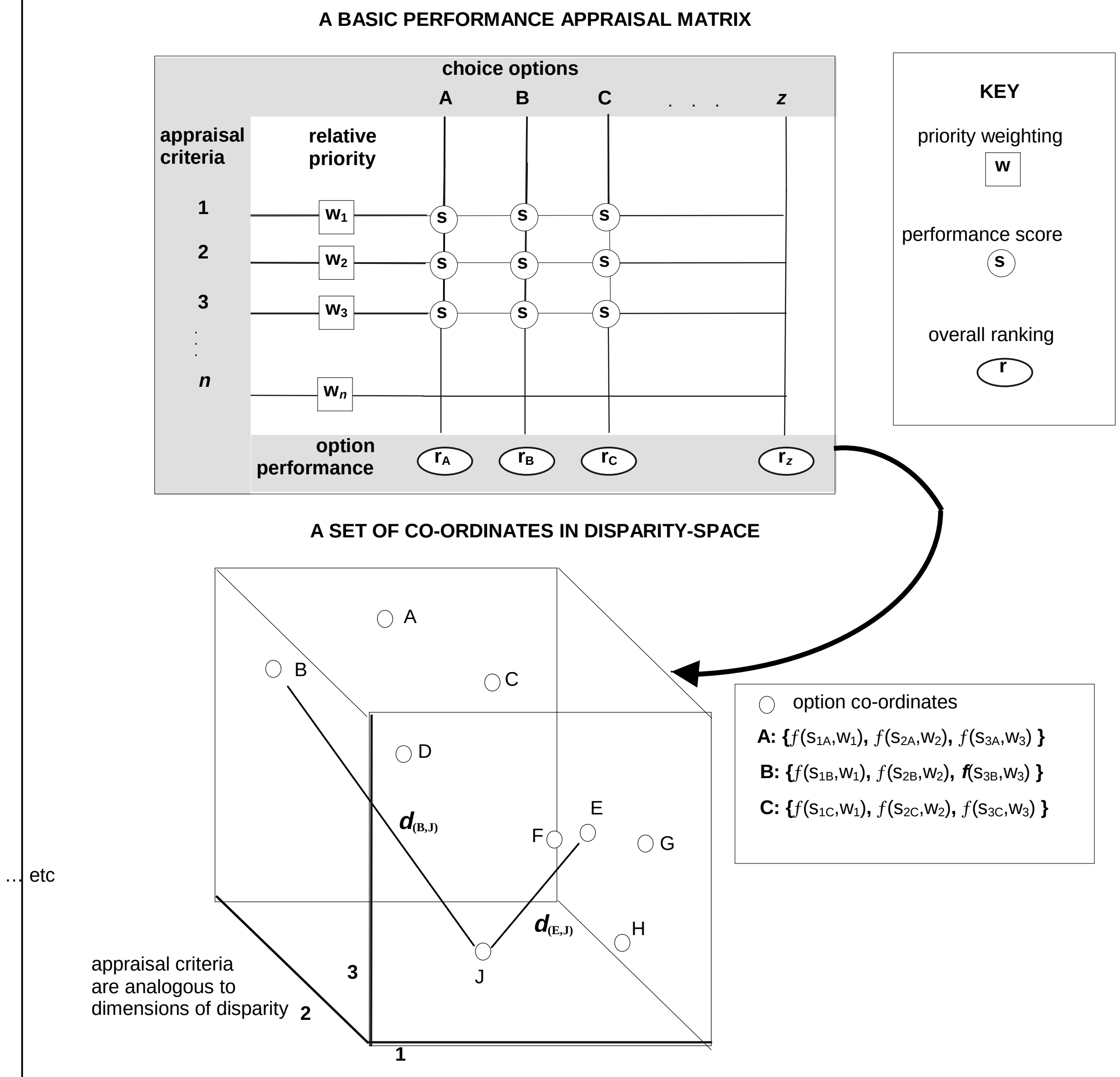
[445] Although the type of criteria and the metrics differ in each case, the principal of aggregation over a range of different criteria applies in all these (and other) approaches to appraisal.

[446] The point is that there is an analogy, not an identity. In some respects, the resulting array of ratings under ***n*** different appraisal criteria might also be taken as a basis for a crude representation of option disparities in terms of a distribution of points in a corresponding ***n***-dimensional disparity-space (scaled according to the criteria weighting functions). However, this would lead to perverse outcomes, in that options which are in all respects identical to others except for radically poorer performance under one criterion would simply on the grounds of this poor performance, be counted as displaying a corresponding disparity (and thence, diversity) benefit. For this reason, although directly analogous, the characterising of performance and disparity should be independent. In practice, disparity attributes are likely to make reference to different factors and be weighted differently than the appraisal criteria employed in the evaluation of individual option performance. It is thus the general structure of the problem, rather than the specifics, which are analogous.

Box 16: An analogy between performance matrices and co-ordinates in disparity-space



One of the principal problems in the various approaches to the characterisation of disparity reviewed in the last section lay in the need for what must inevitably be a somewhat subjective, even *ad hoc*, choice of framing assumptions from amongst the vast array of possible attributes which might be applied to the classification of option disparities. What is interesting, is that exactly the same predicament underlies appraisal itself. No matter what technique is employed, any act of appraisal requires the adoption of a particular perspective on the choice of performance criteria, their prioritisation and the rating of option performance under each criterion. Indeed, it was precisely this predicament which underlay the discussion earlier in this paper of the value of diversification as a response to the problems of social choice theory [447]. The point is, therefore, that although any given scheme for characterising the disparity of a particular set of options is intrinsically subjective and context dependent, it is in principle no more so than is the choice of criteria and their prioritisation for the purposes of appraisal itself. The consideration of diversity thus introduces no conceptual difficulties of a kind which are not already intrinsic to appraisal itself.

With a practical context for the heuristic characterisation of disparity thus sketched, attention might turn again to the vexed question of the geometry of disparity-space raised in the last section of this paper. In particular, what would be the implications of assuming that disparity-space displays a familiar Euclidean geometry, rather than the ultrametric structure assumed by Weitzman? The first implication might be greater generality. The ultrametric inequality is, as discussed in the last section, more restrictive in nature than is the triangle inequality associated with Euclidean space [448]. All else being equal (and in the absence of detailed information concerning the particular disparity-generating mechanisms at work in the system in question) this feature might inherently be expected to restrict the empirical applicability of an ultrametric disparity-space compared with a Euclidean disparity-space. The question must be whether or not a Euclidean disparity-space is of greater practical or heuristic use than is the ultrametric geometry employed by Weitzman?

The answer to this crucial question requires some consideration of the nature of the disparity measures employed under each individual criterion. If a distance measure is 'metric', in the sense that associated attributes are fully quantified on a cardinal scale, then it is clear that all options can be represented as points in a Euclidean space [449]. However, some of the attributes of the different options under scrutiny may display characteristics that can be registered only in 'nominal' or 'ordinal' terms. Nominal characteristics are those

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[447] In section 1.4.

[448] To summarise note 428 above: an ultrametric geometry requires that, for a trio of options i, j and k with distances in disparity space indicated by $\mathbf{d}$: $\mathbf{max}\ \{\ \mathbf{d}(i,j),\ \mathbf{d}(j,k),\ \mathbf{d}(i,k)\ \}\ =\ \mathbf{mid}\ \mathbf{d}(i,j),\ \mathbf{d}(j,k),\ \mathbf{d}(i,k)\ \}$. In a Euclidean space, by contrast:

$$0 \leq \mathbf{max\{d}(i,j),\mathbf{d}(j,k),\mathbf{d}(i,k)\mathbf{\}} - \mathbf{mid\{d}(i,j),\mathbf{d}(j,k),\mathbf{d}(i,k)\mathbf{\}} \leq \mathbf{min\{d}(i,j),\mathbf{d}(j,k),\mathbf{d}(i,k)\mathbf{\}}.$$

Cf: Weitzman (1992:368); Rammal, Toulouse and Virasoro, (1986); Bradshaw (1996).

which are subject simply to labelling, with no necessary implications for the ordering of options (an example might be the presence or absence in a given engineered system of different types of component). Ordinal characteristics are those which may be placed in a ranked sequence, but with no notion of ratios or scaling (an example might be aesthetic impacts due to different types of land use).

In the case of nominal or ordinal characteristics, then, distances in an associated disparity-space will be entirely non-metric in nature. In a review of the problems involved in characterising molecular diversity in the field of pharmaceutical research, Bradshaw cautions that "[g]iven a data matrix containing non-metric or mixed variables, it is seldom meaningful to use Euclidean (ie: classical geometric) distances to measure the distances of objects" [450]. Indeed, under such nebulous conditions, it is unlikely that the routine adoption of any other particular type of geometry for disparity-space (including an ultrametric structure) would in general allow for consistently better results than would a Euclidean geometry.

However, when the characterising of disparity is placed in the normative context of performance appraisal, these difficulties are also put in perspective. Unless it is to fall foul of the criticism of 'treating things that are countable as the only things that count' [451], appraisal must necessarily - and routinely - handle nominal and ordinal characteristics. Although it may *not* be possible to derive any comprehensive 'objective' metric ordering for such characteristics, it *will* be possible to determine some distinction on the basis of the preferences displayed under a particular perspective in appraisal. Of course, different perspectives will yield different preference orderings for nominal and ordinal characteristics. Indeed, where preferences are 'non-monotonic' with performance ratings under individual criteria, the same might even be true of relatively robust *metric* criteria [452]. When viewed against the scope for vagaries and complexities in the assignment of

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[449] The point is noted, for instance, by Solow, Polasky and Broadus, 1993.

[450] Bradshaw, 1996. Giving the example of the combination of amyl and phenyl units in organic chemistry, Bradshaw also makes an argument to the effect that the triangle inequality of Euclidean geometry is itself artificial because it requires that an option (**A)** be considered similar to an option (**C)** simply because both are similar to a third option of intermediate disparity (**B)**. However, such a situation is as much a function of the attributes employed in characterising disparity as it is of the geometry of disparity space. If a broader range of attributes are recognised, including those exclusively displayed by **A** and those exclusively displayed by **C**, then the disparity distance between **A** and **C** will correspondingly increase (Bradshaw, 1996).

[451] To paraphrase a remark of Holdren's (1982) quoted in Section 2.3.2.

[452] This is the condition under which two variables co-vary in opposite directions at different values. An example here might be physical concentrations of certain ozone-precursor pollutants in the atmosphere, where intermediate concentrations are thought to be more harmful than high or low concentrations (Brooks, 1986). Alternatively, the same might be true of the preferences of managers concerning the scale of an industrial installation.

preference functions to this kind of performance criterion in appraisal, concerns over the ‘nominal’, ‘ordinal’ or ‘metric’ status of different disparity attributes can become rather scholastic.

The implications of all this for assumptions over the geometry of disparity-space are quite profound. The central insight which arises from the consideration of appraisal, is that it is futile to aspire to any ‘objective’ (or in some other way definitive) configuration of co-ordinates in disparity-space. Notions of disparity in each particular case will be a function of the selection and prioritisation of the different attributes that are felt to be of relevance in any given context, just as much as they are of any metric ratings under these attributes. Since the assignment of weightings to the disparity attributes is as intrinsically subjective as the assignment of priorities to performance criteria, the particular values arrived at under any given perspective will be irreducibly context-dependent in each exercise.

Once a set of disparity attributes has been selected and prioritised, however, each potential portfolio of the options under appraisal may be associated with a single, precisely-specified set of co-ordinates in disparity-space. Changes in the weighting schemes assigned to the disparity attributes might be expected to exert similar impacts on distances in disparity space to those which would result from divergent assumptions over the geometry of that space [453]. Conversely, the effects of assuming different geometries might alternatively be represented by transformations in the scaling of the dimensions of the disparity-space, such as those that arise through the adoption of different weighting schemes. In this light, all that can reasonably be required of assumptions over the geometry of disparity-space is that they be relatively *simple* (ie: involving a minimal number of extraneous parameters, constraints and assumptions), *transparent* (ie: readily communicated and meaningful to all interested parties) and *neutral* (ie: not imposing any systematic methodological bias with respect to the apparent relative disparities of different options).

The conclusions for the characterisation of disparity, then, though highly qualified, are quite straightforward. Just as there can be no single objective or definitive ordering of options in terms of overall performance, so there can be no final authoritative ruling on the relative merits of adopting different geometries for disparity-space. When spurious aspirations to synoptic objectivity are set aside, a systematic framework for the characterisation of disparity is - like any formal analytical scheme for the evaluation of performance - ultimately better seen as a *heuristic* than as a definitive procedure [454]. However, this does not negate the normative value of such a framework. Just as some rank orderings of options will be more robust than others under changing priorities in appraisal, so certain geometries of disparity-space will be generally more applicable. In this light, the familiar and relatively permissive characteristics of a Euclidean geometry look significantly more attractive than the rather idiosyncratic and restrictive specifications of an ultrametric geometry. Different possible approaches to the characterisation of disparity may – like different perspectives in appraisal more widely – be addressed by means of a reflexive procedure which iterates repeatedly between the setting of framing assumptions and the examination of results. At the very least, the approximation to metric disparity measures required of a Euclidean assumption seems less contrived than the assumption of exclusively bifurcating lineages of the kind implied by an ultrametric geometry.

Unless there are good reasons to the contrary, then, it therefore seems to make sense to proceed on the basis of a working assumption that the property of disparity might - at least for the heuristic purposes of appraising economic options such as investments, technologies and policies - generally be represented (under a particular perspective in a particular context) as a distance in a Euclidean multi-criteria disparity-space.

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[453] This amounts effectively to an assumption that any change in the geometry of disparity-space may be expressed in terms of a transformation in the weighting functions applied to the various disparity attributes.

[454] The term ‘heuristic’ is employed here to suggest a framework for the systematic exploration of a problem, rather than the achievement of a single uniquely definitive resolution.

3.2 Properties of an Integrated Multicriteria Diversity Index

Having established a general framework for the heuristic characterisation of disparity, attention may turn finally to the integrated measurement of diversity as a whole. Based on the preceding discussion in this paper, a number of criteria may be resolved against which to judge the practical efficacy of any candidate general integrated index of diversity. These may be defined and clarified by reference to the principal diversity measures that have been discussed so far: the Shannon and Simpson indices of dual concept diversity; Junge's 'triple concept' diversity measure and Weitzman's disparity index.

First, any candidate diversity measure should be ***complete***, in that it should address at the same time the variety, balance and disparity components of diversity. Both Shannon and Simpson are restricted to variety and balance. Weitzman's measure is restricted to disparity alone. Of the approaches reviewed in this paper, only Junge's 'triple concept' diversity measure aspires to this property of completeness. No other diversity index known to the present author satisfies this criterion.

Second, the measure should be ***parsimonious***, involving *only* those types of variable or operation which are already required in the appraisal of contending options. To the extent that the disaggregation of options is an unavoidable requirement in appraisal, both the Shannon and Simpson indices are relatively parsimonious. The only variables required in applying these indices are the concept of proportional representation and the disaggregation of option classes. Although the algorithm which operationalises the Weitzman index is quite complex (both in form and in computation), the concept itself is, in fact, relatively parsimonious. It is based, essentially, on the straightforward concept of a 'distance' between different attribute values under different criteria such as those routinely employed in appraisal. Junge's 'triple concept' diversity measure, by contrast, requires the characterising and measurement of numerous ancillary data such as the standard deviations in the statistical distributions of characteristics and is sensitive to the values taken by exogenously imposed parameters such as the number of classes of options recognised (cf: Box 13). Junge's measure is therefore correspondingly lacking in parsimony.

Third, the measure should be ***transparent***, requiring a minimal number of hidden assumptions concerning the natures and structures of the systems under scrutiny. Unlike ‘parametric’ approaches to dual concept ecological diversity, the ‘non-parametric’ Shannon and Simpson functions do display this property. Junge’s ‘triple concept’ diversity measure does not, since the dependence on such a wide variety of input variables introduces hidden sensitivities as well as those that are explicit. The restrictive consequences of the assumption that disparity may be modelled as an ultrametric geometry mean that Weitzman’s disparity measure is also relatively non-transparent in this sense.

Fourth, the measure should be ***robust***, in the sense that the orderings obtained should not be sensitive to changes in the value of those parameters that are included. The family of possible Shannon functions addressed in Box 11 [455], for instance, are *robust* measures of dual concept diversity. This is because the orderings that they generate are not sensitive to the particular logarithm base that happens to have been chosen by the analyst. The family of possible Simpson functions displayed in Box 11, however, are *not robust* in this sense. This is because the choice of different exponents implies the assignment of a different relative weighting to variety and balance, potentially altering the rank orderings for the systems under scrutiny. Given the number of highly determining variables and parameters involved, Junge’s triple concept measure seems especially lacking in robustness. For those systems that are satisfactorily modelled as bifurcating lineages, Weitzman’s disparity measure is arguably highly robust. For those systems that are *not* well modelled in this way, his index is correspondingly not robust.

Of course, as is true of any appraisal, the formulation and application of a set of criteria such as these is necessarily quite subjective and context-dependent. Although the criterion of completeness is pretty clear-cut, the precise formulation of the criteria of transparency, parsimony and robustness - and the evaluation of the relative merits of different indices under these criteria - are simply those of the present author. Similarly, there are senses in which compliance with the different criteria are to some extent in conflict. For example, the extension of analytical scope required by the criterion of completeness is clearly in conflict

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[455] Section 2.2.

with the other criteria. Transparency, parsimony and robustness might all more readily be fulfilled where the scope of the analysis of diversity is narrowed.

Likewise, though transparency, parsimony and robustness are all to some extent related, they may also be in conflict. For instance, if analysis is undertaken systematically to explore different relative weightings on variety and balance, then differences in the results obtained under different Simpson exponents would render this more transparent than Shannon. On the other hand, if (as is more common[456]) analysis is seeking simply to characterise diversity as a whole, with no firm basis for adopting one relative weighting on variety and balance rather than any other, then this transparency becomes a lack of parsimony and robustness, and the Shannon function is preferable.

The results of this informal appraisal of the different diversity measures are summarised (in Box 18) when a novel ‘triple concept’ diversity index is proposed later in this section. For the moment, although there may be differences of interpretation on specifics, this set of four criteria for the evaluation of key existing candidate diversity indices does fulfil some useful functions. It highlights in a systematic way the practical shortcomings in all the various diversity indices that have been reviewed in this paper. Also, it offers an explicit account of the underlying basis for the present approach to the characterising and measurement of diversity. To this extent, critical review of these criteria should at least serve the purpose of permitting more detailed criticism of any proposals that are to be made on this basis.

Before discussing one such specific proposal, however, there is a fifth criterion that must be explored. This concerns the ***consistency*** with which a diversity index addresses the subordinate properties of diversity: variety, balance and disparity. In order to judge consistency, it is necessary that the concepts be characterised more precisely and more formally than the narrative discussion in Section 2.1 and 3.1 of this paper. Accordingly, mathematical expressions for each of these properties are suggested in Box 17[457].

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[456] The author knows of no case in the literature reviewed for this paper where this is an explicit feature of analysis.

[457] Alternative formulations might be based on logarithmic conceptions of variety ($\ln \Sigma_i p_i^0$) and balance ($-\Sigma_i p_i \ln p_i / \ln \Sigma_i p_i^0$).

Box 17: A set of formal expressions for the properties of variety, balance and disparity

(cf: Section 2.1).

Where: p_i = the proportional representation of option i.
$\boldsymbol{d}_{ij}$ = the distance in a Euclidean disparity-space between options i and j.

variety: $\boldsymbol{V} = \sum_i p_i^0$ the number of options in the portfolio
(high ***V*** indicates high diversity).

balance: $\boldsymbol{B} = \frac{1}{V}\sqrt{\sum_i\left(p_i - \frac{1}{v}\right)^2}$ a measure of the aggregate degree of
'variance' in the p_i
(low ***B*** indicates high diversity);

disparity: $\boldsymbol{D} = \sum_{ij} \boldsymbol{d}_{ij}$ the sum of Euclidean distances between
pairs of options in 'disparity-space'
(high ***D*** indicates high diversity).

Accordingly (and unlike the other criteria), the criterion of consistency may be characterised in quite formal terms. Although others might be identified, the principal elements of consistency from the point of view of the present account are as follows.

(*i*) For a portfolio of evenly balanced, equally disparate options, the diversity index should increase monotonically with variety [458].

(*ii*) Where variety is equal to one, the diversity index should take a value of zero.

(*iii*) For a portfolio of given variety and disparity, the diversity index should increase monotonically with the degree of balance in the spread of option contributions (ie: the diversity index should take a maximum value at any given level of variety and disparity where all options are represented equally).

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[458] Links with Weitzman's (1992) *monotonicity* property.

(iv) For a portfolio of given variety and balance, the diversity index should increase monotonically with the aggregate distance between options in 'disparity-space' [459].

(v) Where this aggregate distance is zero (ie: where all options are effectively identical), the diversity index should take a value of zero [460].

Taken together, these criteria and the definitions adopted for the subordinate properties of variety, balance and disparity in Box 17 *do not* appear to provide a sufficient basis for the rigorous definition from first principles of a single uniquely authoritative algorithm [461]. However, they do suggest a quite compelling and straightforward initial response to the problem of deriving a complete, transparent, parsimonious, robust and consistent diversity index. For, there are just two basic defining elements in the three subordinate properties of diversity illustrated in Boxes 5 and 6. These are the proportional representation of each respective option and the distance separating each pair of options in disparity-space [462]. ***An obvious starting point candidate for an integrated index of diversity might therefore be the product of these two basic elements*** **[463]**.

A formal expression for such an index is reproduced in mathematical notation in equation [5] below. Since the key distinguishing features of this approach are the integration of variety, balance and disparity and a multi-criteria concept of disparity (drawn from an analogy with multi-criteria appraisal), this function might be called an 'integrated multicriteria diversity index', ***M***:

$$\boldsymbol{M} = \sum_{ij} \boldsymbol{d}_{ij} . p_i . p_j \qquad [5]$$

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[459] Links with Weitzman's (1992) *continuity* property.

[460] Links with Weitzman's (1992) *twinning* property.

[461] At least, such a proof lies beyond the mathematical competence of the author, who awaits with interest correction on this point.

[462] In other words, whatever is defined for the purpose of any given piece of analysis as an appropriate configuration for disparity space.

[463] In actual fact, the original conception of this idea followed pretty much exactly this line of reasoning, and occurred to the author prior to any knowledge of the use of dissimilarity-distance metrics such as those of Weitzman (1992), Solow, Polasky and Broadus (1993) or Humphries, Williams and Vane-Wright (1995).

Where (as in Box 17 and elsewhere in this paper): p_i is the proportional representation of option i and $\boldsymbol{d}_{ij}$ is the distance in a Euclidean disparity-space between options i and j (as illustrated in Box 16). In other words, the integrated multicriteria diversity of a portfolio of options might formally be specified as ***the product of the disparity-distance of each pair of options and the proportional contributions to the portfolio of each member of that pair, summed over all pairs of options***. Since disparity-distances are entirely symmetrical for each pair of options, there will for any set of $\boldsymbol{z}$ options be a single unique array of $(\boldsymbol{z}^2-\boldsymbol{z})/2$ disparity-distances [464].

What is interesting, is that this rather obvious intuitive response to the problem of characterising diversity also seems to go further than the other indices so far discussed in satisfying the criteria set out above. It is ***complete***, in that it addresses directly the variety, balance and disparity components of diversity. It is relatively ***transparent***, both because it is non-parametric and because the use of a Euclidean disparity-space is less restrictive than, say, an ultrametric geometry. It is ***parsimonious***, because it relates exclusively to the properties of options (performance criteria and disparity attributes) which are already of interest in appraisal. Finally, it is relatively ***robust***, since it is not dependent on a choice of essentially arbitrary parameter values such as logarithm bases or exponential powers. Even the distance measure is less ambiguous than is that employed in the Weitzman function [465]. Above all, this concept of an integrated multicriteria diversity index is (despite its name!) quite remarkably *simple*, in the sense that it is both readily expressed and quite easily understood.

In appearing to satisfy better the criteria of completeness, transparency, parsimony and robustness, the integrated multi-criteria diversity measure ('$\boldsymbol{M}$') already appears to display significant advantages over the other indices of diversity that have so far been considered in this paper. However, if it is to offer an effective practical tool, $\boldsymbol{M}$ must also satisfy the criterion of consistency. Here, a useful frame of reference might be to compare under each requirement specified above, the performance of $\boldsymbol{M}$ and those of the

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[464] The magnitudes of these disparity-distances will reflect the ratios in the weightings assigned to the various disparity attributes and so may be scaled to any convenient value. It is the ratios between the differences in these distances that is important. Perhaps the most suitable basis for normalisation would be to set the total aggregate disparity ($\boldsymbol{D}$ in Box 17) at unity, and express each element ($\boldsymbol{d}_{ij}$) as a fraction of this.

[465] Because it is calculated on a simple pairwise basis, rather than in terms of one amongst a number of possible element-to-group conventions (such as 'nearest neighbour', 'furthest neighbour' or 'centre of gravity').

Shannon function (concluded earlier to be the most promising candidate as a general index of dual concept diversity [466]) and Weitzman's disparity measure (which - as has been discussed - holds many important lessons for the characterising of disparity) [467].

With regard to requirement (*ii*), it follows automatically from equation [5] that (as with both Shannon and Weitzman indices), where variety is equal to one, ***M*** will be equal to zero [468]. Similarly, with requirement (*v*), it is a self-evident consequence of equation [5] that where the inter-option disparity distances ($\boldsymbol{d}_{ij}$) are zero, ***M*** will also be equal to zero [469]. Weitzman also satisfies this requirement. However, since Shannon is entirely insensitive to disparity, it does not display this property.

As may be demonstrated empirically [470], the properties of ***M*** also comply with requirements (*i*) and (*iii*) and (in fact) are actually quite similar to those of Shannon. For portfolios of evenly balanced, equally disparate options, ***M*** is seen to increase monotonically with variety, displaying slightly less sensitivity than Shannon to incremental increases at higher levels of variety. Likewise, for portfolios of given variety and disparity, ***M*** also increases monotonically with the evenness in the balance of option contributions, again displaying slightly less sensitivity than Shannon for increases in balance in the most balanced portfolios. The Weitzman index is, of course, entirely insensitive to changes in either variety or balance. Finally, with regard to requirement (i*v*) concerning disparity, for portfolios of given variety and balance, it may be shown empirically that ***M*** also increases monotonically with the aggregate distance between options in 'disparity-space'.

The properties of the Shannon, Simpson, Junge, Weitzman and ***M*** indices under criteria of completeness, parsimony, transparency and robustness (as well as the more formal conditions discussed here) are summarised in Box 18. Taken together, it seems possible to draw some quite surprisingly clear conclusions concerning the integrated multicriteria diversity index ***M***. Although it may not be possible formally to

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[466] Equation [2] in Section 2.2: $\boldsymbol{H} = -\sum_i p_i . \ln p_i$,

[467] Equation [4] in Section 2.3.3: $\boldsymbol{D}_W(S) = \max_{i \in S} \{ \boldsymbol{D}_W(S \setminus i) + \mathbf{d}_W(i, S \setminus i) \}$

[468] This is because where $p_i = 1$, $p_j = 0$. With each product thus being equal to zero, the overall sum must be zero.

[469] Again, because with each product being equal to zero, the overall sum must be zero.

[470] As performed in an unpublished working paper by the author.

derive this (or, indeed, any other) single uniquely authoritative index from some basic set of mathematical principles in order to satisfy the various operational criteria that have been resolved in this section, it does seem that ***M*** displays some significant practical advantages when compared with other indices in the published literature. In short (and in the terms defined here) ***M*** appears to be the only extant potential general measure of diversity which is at the same time complete and consistent, as well as being relatively transparent, parsimonious and robust. On these grounds alone, then, it seems that this relatively straightforward concept may deserve serious further attention as a potentially useful heuristic and analytical tool in the measurement and more detailed economic evaluation of diversity.

Box 18: Summary of some key factors in the choice of a heuristic index of triple concept diversity

	SHANNON $-\sum_i p_i.\ln p_i$	SIMPSON $\sum_i p_i^2$	JUNGE Cf: Box 13	WEITZMAN max $\boldsymbol{D}(S\backslash i)+\mathbf{d}(i,S\backslash i)$	*M* $\sum_{ij} \boldsymbol{d}_{ij}.p_i.p_j$
COMPLETENESS	░	░	■	░	■
PARSIMONY	■	■	░	■	■
TRANSPARENCY	■	■	░	▒	■
ROBUSTNESS	■	▒	░	▒	■
CONSISTENCY					
(i) monotonic with changing variety	■	■	▒		■
(ii) null value for variety of one	■	░	▒	■	■
(iii) monotonic with changing balance	■	■	▒		■
(iv) monotonic with changing disparity			▒	■	■
(v) null value for zero disparity			▒	■	■

PROPERTIES OF INDEX

■ **good** ▒ **intermediate** ░ **poor** **not applicable**

3.3 Optimising Diversity and Performance

It has been argued in this paper that the deliberate diversification of economic options may offer benefits in terms of the fostering of innovation, the hedging of ignorance, the mitigating of lock-in and the accommodation of divergent values. Nevertheless, the diversity of a portfolio of investments, technologies or policies is just one aspect of the economic performance of any portfolio taken as a whole. In most cases, the dominant factor in the overall performance of a portfolio of economic options will be a function of the performance of the individual options themselves. Indeed, in cases where one (or a small group) of options offer radically superior performance to any others, it is likely (and entirely reasonable) that diversity will play a small - even insignificant - part in economic appraisal.

The same is true, of course, where little value is attached to the strategic benefits variously claimed for diversity. However, as the relative value of diversity is seen to increase, the crucial issue becomes one of the trade-offs that must exist between diversity and the other aspects of wider economic performance. As has been discussed earlier in this paper, factors such as economies of scale, transaction costs and the benefits of standardisation must be set against any benefits that diversity may be held to confer [471]. The question therefore is, how might we go about systematically exploring the various possible trade-offs between diversity and other aspects of performance in a portfolio of economic options under different possible conditions?

The notion of an ‘optimal’ trade-off between diversity and other aspects of performance is, of course, potentially highly misleading. In just the same way that performance rankings of individual options will always involve subjective and context-dependent assumptions concerning the framing of analysis, the choice of appraisal criteria and their prioritisation, so too will the identification of an ‘optimal’ trade-off between diversity and performance be a necessarily highly circumstantial undertaking. Nevertheless, where it is possible to identify a robust and precisely specified measure of diversity (such as ***M***), then, *for any given set of options, criteria, priorities and framing assumptions*, it *will* be meaningful to speak of a single unique

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[471] These issues are discussed in more detail in Section 1.1.

'optimal' trade-off between diversity and performance. The analysis of the way such trade-offs vary with changing assumptions is - under such conditions - no more intractable in principle than is the appraisal of more traditional notions of economic performance under multiple social or policy criteria. Accordingly, the business of balancing the aggregate performance of individual options (on the one hand) and portfolio diversity (on the other) might be termed '***diversity optimisation***'. For any given set of options, under any given set of circumstances, there will exist a single hypothetical '***diversity-optimal portfolio***' with respect to the performance appraisals available to each individual analyst, decision-maker or interested third party, together with their respective aversions to ignorance and lock-in and desires for innovation and pluralism.

Under circumstances where no value at all is placed on diversity, then the diversity-optimal portfolio will comprise a one hundred per cent contribution by that option which displays the best overall performance under other performance criteria. Where a zero weighting is placed on diversity, successively poorer options begin to make contributions to a diversity-optimal portfolio in sequence of diminishing performance only if the contributions of better-performing options are constrained. As the relative priority attached to diversity increases, however, then lower-performing options are included in the diversity-optimal portfolio before the possible contributions of better-performing options have been exhausted [472]. The proportional representation of each option in the diversity-optimal portfolio will represent a balance between the priority assigned to diversity, the performance of the various options under other appraisal criteria, the priorities that are assigned to these criteria and any constraints that there may be on the contributions which may be made by individual options.

In other words, where a non-zero value is attached to diversity, any diversity-optimal portfolio of investment, technology or policy options will display a lower overall performance under other criteria than would be the case if only the best-performing options were included to their maximum possible contributions. Following widely established practice in energy economics, the resulting sacrifice in aggregate portfolio performance might be seen as a '***diversity premium***'. The magnitude of the diversity premium which a decision maker will be willing to pay will, in general, reflect assessments of the importance of factors such as ignorance, value pluralism, avoidance of lock-in and the fostering of innovation, relative to the other dimensions in the performance of the individual options under consideration [473].

One way of looking at this problem of diversity optimisation might be in terms of the maximising of utility. Under this view, the performance of any group of investment, technology or policy options under a set of prioritised appraisal criteria confers utility. For the purposes of exposition, the present account will employ what is arguably the most straightforward of multicriteria frameworks - a ‘linear additive weighting’ procedure (cf: Box 16 [474]). Under this procedure, the performance rank of an individual option ($\boldsymbol{r}_i$) is given as the product of (suitably normalised) performance scores under each individual criterion ($\boldsymbol{s}_{ic}$) and the importance weighting assigned to each respective criterion ($\boldsymbol{w}_c$), summed over all criteria:

$$\boldsymbol{r}_i = \sum_c \boldsymbol{w}_c . \boldsymbol{s}_{ic} . \qquad [6]$$

Where the scope of analysis is confined to narrow economic factors, of course, the performance ranks ($\boldsymbol{r}_i$) may simply be a reflection of costs. However, a straightforward multi-criteria framework offers the benefits of greater generality, since it can equally be reduced to a narrow cost-benefit frame or extended to address virtually any conceivable criterion under which it is possible to appraise option performance [475].

In these terms, then, that portion of the overall utility of the portfolio as a whole which is due to the performance of the individual options ($\boldsymbol{U}_{opt}$) is given by the performance rank ($\boldsymbol{r}_i$) of each option, weighted by the proportional representation of that option in the portfolio ($\mathbf{p}_i$), summed over all options:

$$\boldsymbol{U}_{opt} = \sum_i \boldsymbol{r}_i . \mathbf{p}_i \qquad [7]$$

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[472] This point is pertinent where options involve the consumption of some limited resource and is elaborated in the next section.

[473] Stirling, 1994.

[474] Such as that outlined in Section 3.1.

[475] Some of the issues associated with the use of a multi-criteria framework in appraisal are discussed in Stirling, 1996, 1997.

However, depending on judgements as to its value as a means to foster innovation, hedge ignorance, mitigate lock-in and accommodate pluralism, diversity may be held also to confer a certain amount of utility in a portfolio of economic options in and of itself. Here the contribution to overall portfolio utility due to the diversity of that portfolio may be expressed in terms of a diversity index (such as $\boldsymbol{M}$), scaled in a fashion which makes it commensurate with the utility due to the performance of individual options ($\boldsymbol{U}_{\text{opt}}$) given in Equation [7]. In these terms, the diversity-optimal portfolio might formally be conceived as that particular mix of options for which the sum of the utility of the individual option performances and the utility of the diversity of the portfolio as a whole takes some maximum value. Such a utility maximisation function for the purposes of diversity-optimisation might take the following form:

$$\max(\boldsymbol{U}_{\text{prt}}); \quad \boldsymbol{U}_{\text{prt}} = \boldsymbol{U}_{\text{opt}} + \boldsymbol{U}_{\text{div}} \qquad [8a]$$

$$= \boldsymbol{U}_{\text{opt}} + \delta.\mathit{\Delta} \qquad [8b]$$

Where $\boldsymbol{U}_{\text{prt}}$ is a measure of overall portfolio utility, $\boldsymbol{U}_{\text{opt}}$ is the contribution to overall portfolio utility due to the performance of the individual options (given in Equation [7]) and $\boldsymbol{U}_{\text{div}}$ is the contribution to overall utility due to the diversity of the portfolio. As is shown in Equation [8b], this latter term can be expressed by means of a suitable diversity index, with $\mathit{\Delta}$ representing the value taken by such an index and δ representing a coefficient which scales this index to values commensurate with $\boldsymbol{U}_{\text{opt}}$.

In earlier work making use of the Shannon index of dual-concept diversity, the present author has explored in some detail the application of such a model to the practical task of the strategic appraisal of UK electricity supply options [476]. Where $\mathit{\Delta}$ is identified with the Shannon index (given in Equation [2]) and option performance is appraised under a simple multi-criteria framework (such as that in Equation [7]), the diversity-optimal portfolio is found by solving the appropriately substituted form of the maximisation function in Equation [8b]:

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[476] Stirling, 1994, 1995, DTI, 1995.

$$\max(\boldsymbol{U}_{\text{prt}}); \qquad \boldsymbol{U}_{\text{prt}} = \sum_i \boldsymbol{r}_{\mathbf{i}}.\mathbf{p}_{\mathbf{i}} - \delta.\sum_{\mathbf{i}} \mathbf{p}_{\mathbf{i}}.\mathbf{ln}\ \mathbf{p}_{\mathbf{i}} \qquad [9]$$

In the case where diversity is measured using the Shannon index, It is possible to solve the maximisation function in Equation [9] in a relatively straightforward fashion by the method of indeterminate multipliers to yield a simple general expression for the contribution of option i to the diversity-optimal portfolio ($\mathbf{p^*}_I$) as a function of the overall performance of that option ($\boldsymbol{r}_{\mathbf{i}}$):

$$\mathbf{p^*}_i = \exp(\boldsymbol{r}_i/\delta) \,/\, \sum_i \exp(\boldsymbol{r}_i/\delta) \qquad [10]$$

By paying detailed attention to cost assumptions, by taking account of the form taken by the supply curves for the various ‘renewable’ generating options and by restricting attention to the better-documented financial dimensions of option performance, it was possible by this means to achieve a tolerable degree of realism and so draw circumscribed, but quite robust, conclusions concerning the efficacy of UK Government interventions which were ostensibly aimed at maintaining the diversity of the national electricity supply mix. Of course, since the analysis was based on an index of dual concept diversity, the validity of the results of this (and any other such) exercise are necessarily entirely dependent on the judicious categorisation of options [477]. A corresponding analysis based on the integrated multicriteria diversity index $\boldsymbol{M}$ would not be similarly constrained. Unfortunately, however, the form of $\boldsymbol{M}$ is such that it is *not* possible readily to specify an analogous solution to the utility maximising function in Equation [8] in terms of $\boldsymbol{r}_{\mathbf{i}}$, δ and an array of disparity-distances $\boldsymbol{d}_{ij}$ [478].

In practice, this technical difficulty in applying a utility maximising approach to the optimising of portfolio diversity using the multicriteria index $\boldsymbol{M}$ turns out not to be prohibitive in itself. The reason is, that it is superseded by a number of collectively more serious problems! One such problem concerns the form that the utility maximisation function is assumed to take (Equation [8b]). Although it may be simple and intuitively appealing, there seems no strong reason to assume that this function should be additive (rather

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[477] Cf: Section 2.3.2.

than, say, multiplicative or quadratic) in form. The fact that such additive relations are often assumed in fields such as cost-benefit analysis might invite more lenient judgement, but cannot in itself justify such assumptions.

Another problem concerns the concept of a simple scalar coefficient (δ) linking diversity and performance. Where a diversity optimisation exercise is undertaken just as a heuristic, with the aim simply of systematically exploring the various concepts involved, such questions do not pose undue difficulties. In any case, if diversity has been collapsed onto a dual concept measure such as the Shannon function, concern over such relatively esoteric issues may in any case seem somewhat academic. Where analysis employs a more robust index such as ***M***, however, and where it aims at a comprehensive general overview of a problem in economic diversity optimisation, then it may make sense to apply a more generally applicable framework. One such framework is the concept of 'Pareto dominance'.

The basic idea behind the application of the concept of Pareto dominance to the present problem of diversity optimisation is very simple. As discussed above (and expressed in Equation [8a]), the utility of all possible economic portfolios may be seen to comprise two components: one due to the diversity in the portfolio as a means to address innovation, ignorance, lock-in and pluralism; the other due to the performance of the individual options under whatever appraisal criteria are felt to be important (such as cost, environmental impacts, employment and so on). If these two dimensions of portfolio performance are represented as the axes of a graph, all possible portfolios can be represented as points scattered on the plane of that graph, their co-ordinates given (respectively) by their diversity and the individual option performance component of overall portfolio utility. Where the axes of the graph are scaled in terms of ascending performance and diversity, ***only those portfolios whose co-ordinates lie on the boundary of scatter which is furthest from the origin will display the best overall performance*** [479]. This is the 'Pareto-efficient' frontier for the set of all possible portfolios drawn from that particular set of options under that particular set of weighted appraisal criteria and disparity attributes. Those portfolios that lie on this frontier

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[478] Again, such a feat lies beyond the mathematical competence of the present author!

[479] Strictly speaking, for a convex distribution such as that typically associated with a diversity-performance plot, the points lying on the Pareto frontier are those lying at the furthest *radial* distances from the origin.

are said to '*dominate*' all others, either because they display maximum diversity for a given level of performance, or because they display maximum performance for a given level of diversity [480].

Box 19 provides a schematic illustration of the application of this kind of Pareto dominance approach to the optimisation of economic portfolio diversity. For any set of investment, technology or policy options under economic appraisal, it requires the derivation of an associated data set reflecting performance under a range of weighted criteria and disparity attributes in the sense discussed earlier in this paper (cf: Box 16). The component of overall portfolio utility represented by individual option performance ($\boldsymbol{U}_{\text{opt}}$) may be expressed in multi-criteria terms as in Equation [7] above. This may then be plotted against diversity as measured for the same portfolios using a multicriteria index such as $\boldsymbol{M}$. A Monte Carlo procedure is then used to construct a distribution of points on the graph. Each point represents a portfolio assembled from the available options, with the option contributions ($\mathbf{p}_i$) generated randomly. The greater the number of randomly generated portfolios, the denser the distribution of points on the graph, the finer the resolution in the determination of the Pareto-efficient frontier for that particular set of options and weighted criteria and attributes. Box 19 displays a distribution of some 1,300 randomly-generated portfolios relating to a simple hypothetical three-option system.

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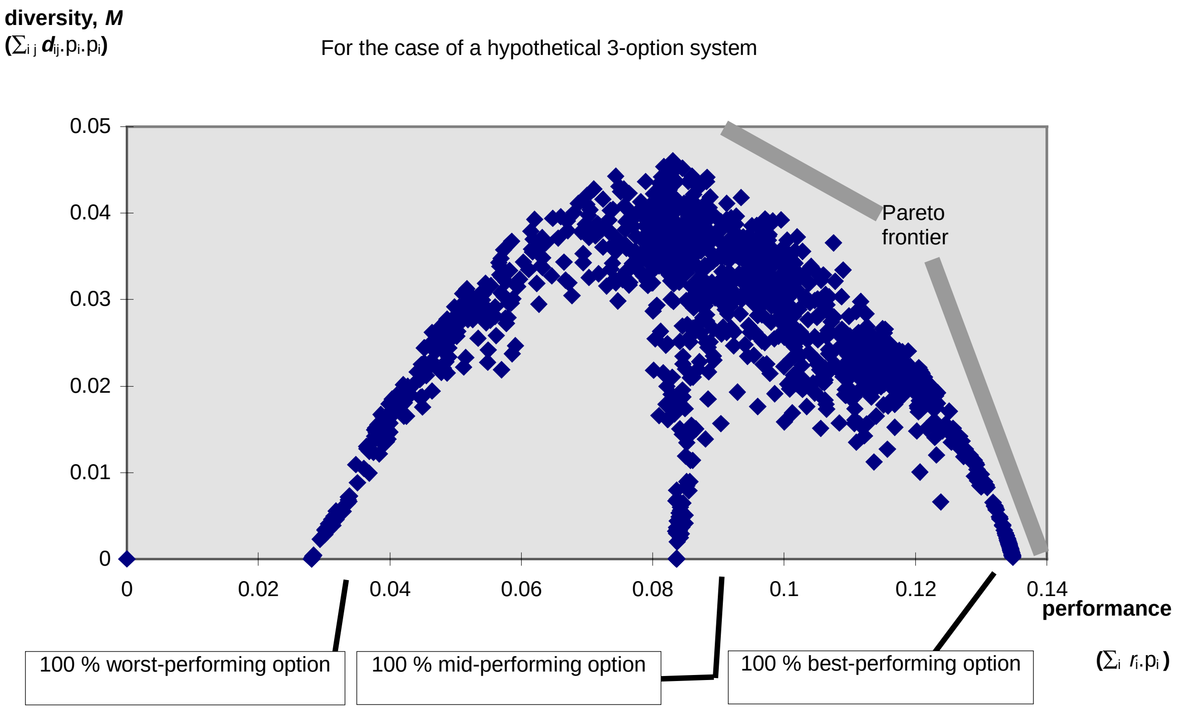
[480] Such approaches are taken to the exploration of diversity / cost trade-offs using different characterisations of diversity in NERA, 1994; ERM, 1994.

Box 19: Analysing trade-offs between diversity and performance with a Pareto dominance approach



As is well illustrated in Box 19, the characteristic form for such a Monte-Carlo plot of diversity against performance for large numbers of randomly-generated portfolios might best be described as a 'jellyfish' - a multiply-concave distribution with a number of tapering 'tentacles' trailing to the performance axis. Since diversity is equal to zero only where the portfolio is comprised entirely of one particular option, it is easy to understand why the jellyfish has exactly as many 'tentacles' as there are options under consideration. The tip of each 'tentacle' represents a portfolio comprising one hundred per cent of one particular option.

Where diversity is characterised in dual-concept terms by means of an index such as the Shannon function, the maximum diversity system will always be comprised equally of all available options. Where diversity is characterised using an integrated multicriteria index such as ***M***, however (as is the case in Box 19), then this cannot be assumed to be the case. Here the composition of the maximum diversity portfolio will reflect the differential disparities between the different available options, as well as the degree of balance in the portfolio as a whole. This is what gives such a rich structure to the plot of diversity against performance such as that shown in Box 19.

The principal feature of interest - the Pareto-efficient frontier - is represented by the curve that bounds the upper right hand side of the distribution in Box 19. This runs from the apex of the distribution (corresponding to the portfolio of maximum diversity) to the portfolio comprised entirely of the best-performing option (corresponding to the portfolio of maximum performance). As we move along this frontier from the apex to the performance axis, we encounter portfolios that are optimal under increasing trade-offs between diversity and performance. The central task under a Pareto dominance approach is thus to identify the composition of all those portfolios which lie along this Pareto frontier. The composition of these dominant portfolios may then be plotted separately, showing how the contributions by different options to the optimal portfolio change in response to variations in the trade-off between diversity and performance. In this way, we can establish for any given set of options, criteria, attributes and weightings a very robust representation of the complete set of all possible optimal portfolios, ***addressing all possible trade-offs between diversity and performance***.

By means of a technique such as this, it is clear that an integrated multicriteria diversity index such as ***M*** may offer the basis for a straightforward and practical method for the systematic analysis of diversity in portfolios of contending investment, technology or policy options. Although the entire procedure may be applied on proprietary spreadsheet software on an ordinary personal computer, this is (as the author can testify!) a rather clumsy and labour intensive operation. A far more elegant matrix optimisation procedure constructed in collaboration with the present author by David Waxman of the University of Sussex using '*Matlab*' proprietary software performs the same operation on a typical personal computer in just a few minutes (for a 12-option, 12-criteria, 12-attribute portfolio) [481]. Results may be exported as a numerical array into a spreadsheet or displayed directly as a graph. When made operational in this way a multi-criteria Pareto-dominance approach to diversity optimisation offers a relatively flexible and transparent analytical

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[481] As expressed in the acknowledgements to this paper, the author is indebted to David Waxman for his work in operationalising the concept of diversity optimisation in this convenient form, without which the results described here could not have been obtained.

and heuristic tool which is readily applicable to a very wide variety of problems in the trading off of diversity and performance in portfolios of economic options.

3.4 Addressing Interactions Between Options

Before turning to a practical demonstration of diversity optimisation using the integrated multicriteria diversity index and real economic data, there is a final potentially highly significant property of the function ***M*** that warrants attention. In order to appreciate the reasons for this, it is necessary to return briefly to the discussion of the economic benefits of diversity addressed in the first section of this paper [482]. The attractions of diversification as a means to hedge against ignorance [483], mitigate 'lock-in' [484] and accommodate plural values [485] are all relatively well captured in the concept of the 'proportional representation' of the different investment, technology or policy options constituting the economic system in question (p_i, p_j in Equation [5] above). However, in considering the possibility that diversity may act to foster innovation, the position is subtly different.

In the case of innovation, it was explained earlier in this paper [486] that much of the current work on economic diversity arises from various forms of network theory. As can be seen from Box 1, the issue in this context is not simply the crude magnitudes of the representation of the different options, but the degree to which they are interconnected in the overarching techno-economic and socio-cultural networks. Although it may in many cases be justifiable to adopt a first order approximation to the effect that the intensity of network interconnections between any two options will be proportional to their respective degrees of representation, a glance at the schematic picture in Box 1 shows how such a state of affairs cannot always be assumed to be the case. The property of network connectivity ***cannot necessarily*** be seen to be well captured by the terms p_i and p_j in the function ***M*** (Equation [5]).

Fortunately, however, the pairwise structure of the function ***M*** *does* provide (where considered necessary) a relatively straightforward way of addressing this potentially important factor. Indeed, this may be another crucial respect in which it appears that ***M*** displays more favourable properties than do many other candidate diversity indices. For, just as is the case with disparity, so the number and intensity of network interactions

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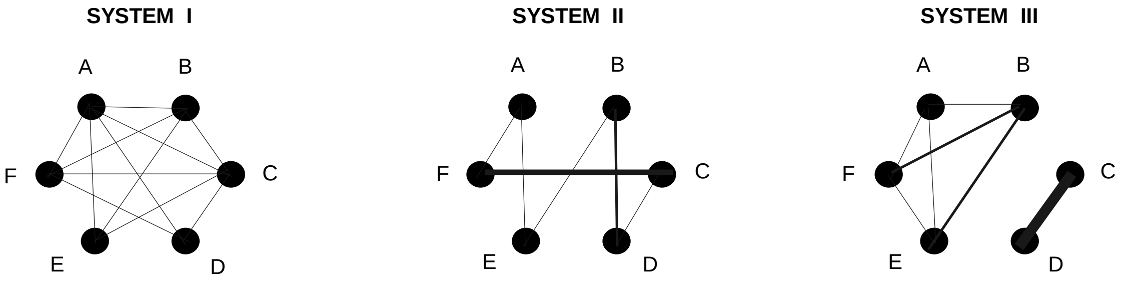
[482] Section 1.
[483] Section 1.2.
[484] Section 1.3.
[485] Section 1.4.

between a set of z options may readily be represented in terms of a $z \times z$ array of scalar numbers. The basic idea is illustrated in Box 20.

Box 20: Characterising network interactions between economic options



The intensity of network interaction
is represented numerically, as follows:

INTERACTION MATRICES

	A	**B**	**C**	**D**	**E**
B	1				
C	1	1			
D	1	0	1		
E	1	1	1	0	
F	1	1	1	1	0

	A	**B**	**C**	**D**	**E**
B	0				
C	0	0			
D	0	2	1		
E	1	1	0	0	
F	1	0	3	0	0

	A	**B**	**C**	**D**	**E**
B	1				
C	0	0			
D	0	0	4		
E	1	2	0	0	
F	1	2	0	0	1

Examples: $i_{BD} = 0$ $i_{BD} = 2$ $i_{CD} = 4$

This construct might be termed an '***interaction matrix***', with the individual elements (i_{ij}) representing the intensity of interactions between each pair of options i and j. Where the network connections are truly reciprocal, then such an interaction matrix will be symmetrical (just as is the case with the disparity-distance matrix) yielding an array of $(z^2-z)/2$ elements. Each of the elements (i_{ij}) in this interaction matrix may serve a purpose which is directly analogous to the disparity distances (d_{ij}), acting as weighting coefficients for the 'proportional representation' terms (p_i, p_j) in the specification of M. The resulting slightly more elaborate function (M') is given below:

$$M' = \sum_{ij} d_{ij}.i_{ij}.p_i.p_j \qquad [11]$$

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[486] Section 1.1.

Of course, as with the disparity term ($\boldsymbol{d}_{ij}$), the elements in the interaction term ($\boldsymbol{i}_{ij}$) must be scaled to some appropriate value, reflecting notions of the relative importance of disparity and option interactions under the perspective in question [487].

The potential utility of the concept of an interaction matrix extends beyond the characterisation of network connectivity alone. For the economic properties of portfolios of investments, technologies or policies often include important operational factors which are not captured either in terms of the performance of the individual options, or in terms of the diversity of the system as a whole. It is often the case that the performance of individual options within a portfolio will be (at least in part) a function of the performance of the other options included in that portfolio. There may be positive synergies between certain options that serve to elevate their combined performance beyond that which would be reflected by the simple sum of their individual performances. Likewise, certain options may be intrinsically mutually incompatible, the presence of one acting to reduce the performance of the other. Box 21 provides some simple examples in this regard from the field of electricity supply portfolios. For the reasons mentioned there, the effective performance of wind power is amplified if combined cycle gas turbines also comprise a large proportion of the electricity system. Likewise, the effective performance of wind power is reduced if a large part of the rest of the system is made up of nuclear power. The economic performance of wind power (for example) thus depends in part on assumptions concerning the mix of options into which it is to be integrated.

The point is, of course, that synergistic portfolio relationships of this sort may also readily be characterised in terms of pairwise interactions. In addition to (or instead of) capturing network connections such as those discussed in Section 1.1, then, the elements in the interaction matrix might be assigned such as to reflect positive or negative operational interactions between the investment, technology or policy options themselves. The precise means by which these disparate aspects of performance might be combined in a single interaction matrix with more abstract notions of network connectivity will, of course, be entirely dependent on the context and purpose of the analysis. In many cases, it is likely that analysis will be

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[487] Since it is the ratios between the magnitudes of these elements that is important, perhaps the most suitable basis for normalisation would be to set the total aggregate magnitude of interaction across the whole system at unity, and express each element ($\boldsymbol{i}_{ij}$) as a fraction of this.

concerned only with one of these factors. Where it is felt necessary to aggregate network connectivity and operational interactions, the determining factors will necessarily vary from case to case. In this respect, the position is no different from the essentially subjective and context dependent determinants in the definition and weighting of performance criteria and disparity attributes. Either way, the details of the analytical procedures employed in this regard are not pertinent for the moment [488]. Here, the essential point is simply that, suitably elaborated (and in addition to its advantages in relation to the characterisation of diversity), the integrated multicriteria diversity index ***M´*** provides in a relatively straightforward form, a means to address a wide range of quite complex properties in economic portfolios.

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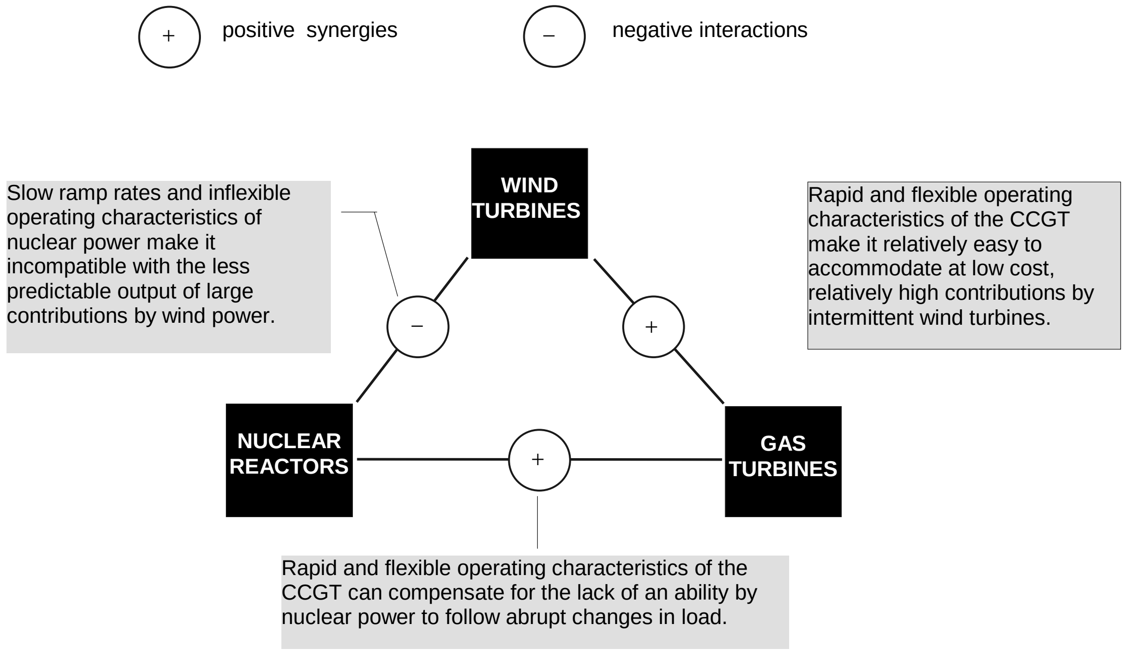
[488] For instance, issues of network connectivity may be expressed simply as a positive number (the greater the connectedness, the larger the number). Synergistic relationships, on the other hand, may (as illustrated in Box 21) take either a positive or a negative form. As shown in Box 21 negative synergies may be represented as weightings of value less than unity and positive synergies as weightings of value greater than unity. The conventions adopted in the aggregation of such terms is a necessary part of the kind of scaling procedure which is always associated with the articulation of such disparate issues.

Box 21: Characterising operational interactions between economic options

an example concerning portfolios of electricity supply technologies



Slow ramp rates and inflexible operating characteristics of nuclear power make it incompatible with the less predictable output of large contributions by wind power.

Rapid and flexible operating characteristics of the CCGT make it relatively easy to accommodate at low cost, relatively high contributions by intermittent wind turbines.

Rapid and flexible operating characteristics of the CCGT can compensate for the lack of an ability by nuclear power to follow abrupt changes in load.

INTERACTION MATRIX

$$\left[\begin{array}{lcc} \textbf{option} & \text{wind} & \text{nuclear} \\ \text{nuclear} & - & \\ \text{gas} & + & + \end{array}\right] \qquad \rule{4em}{0.4pt} \qquad \left[\begin{array}{lll} \textbf{option} & W & N \\ N & \boldsymbol{i}_{NW} < 1 & \\ G & \boldsymbol{i}_{GW} > 1 & \boldsymbol{i}_{GN} > 1 \end{array}\right]$$

Before turning to a practical demonstration of diversity optimisation, there is one final crucial characteristic of economic options (be they investments, technologies or policies) which has not yet been addressed. For just as the elements in a system will interact with each other, so too will they interact with *themselves*. The performance of certain options in a portfolio may display increasing returns to scale. For instance, the capital costs associated with virtually all electricity supply options might be expected to reduce under the volume production economies made possible by larger scale contributions. Other options, however, may show an element of decreasing returns to scale. For instance, the primary resources associated with certain renewable energy options are typically quite site-specific, the best sites displaying significantly better performance than do other possible sites. Such factors can all be captured by characterising the performance of individual options under each criterion, not as discrete numbers, but as a function of the proportional contribution of that option (p_i). In other words, option performance may be modelled as a 'supply curve'.

The easiest way to express a supply curve of the characteristically irregular form associated with real economic options, is to treat each option as an array of separate empirically-defined 'tranches'. Each tranche will be distinguished from its predecessor by some significant discontinuity under a particular performance criterion and so will be assigned a constraint in terms of the proportional contribution to the portfolio at which this discontinuity cuts in [489]. Accordingly, the disparity optimisation procedure will automatically draw first on the best-performing tranche of any option. Once this first tranche is exhausted, subsequent contributions from that option to the portfolio will comprise successively more poorly-performing tranches. Because the integrated multicriteria diversity index (***M´***) characterises disparity independently of any particular scheme for the disaggregation of options (and independently of the performance under appraisal criteria), individual options may be divided up into as many separate performance tranches as is felt appropriate for the purposes of any individual analysis. By the simple addition of constraints, then, a diversity optimisation employing ***M´*** can quite readily be configured in such a way as to address (a least in principle) virtually all pertinent aspects of the performance of economic options.

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[489] Such discontinuities may or may not also be associated with divergences in terms of disparity attributes.

3.5 An Analysis of Diversity in UK Electricity Supply Strategies

3.5.1 The Diversity-Optimisation Procedure

The electricity supply industry is, arguably, the paradigm case of a '***sociotechnical system***' in the sense discussed in Section 1.3 of this paper [490]. It is an industrial sector in which investments are typically large in scale and (increasingly) highly capital- and ***technology-intensive*** [491]. Serious concerns over environmental performance (for example, in relation to radioactive, acid and carbon emissions) are driving a widespread perception of a need for strategic shifts in technology choice, focusing attention on the need for the ***innovation*** of more environmentally benign options [492]. The nature of the technologies and their associated infrastructures is such that they display strong tendencies to increasing returns to adoption, with consequent risks of '***lock-in***'[493]. In addition, the many complex technical, social and physical systems implicated in the performance of the various options (together with the long lead times and plant lifetimes) means that the business of appraisal operates under a pervasive condition of ***ignorance*** [494]. With debates over nuclear power, renewable energy and fossil fuels repeatedly high on the environmental agenda, there are few areas of the economy which have historically displayed such a tendency to the polarisation of ***plural values*** concerning technology choice and investment strategy [495]. In other words, the electricity supply industry offers an example of an area of the economy in which policy is heavily influenced by virtually *all* of the issues raised in the discussion of economic diversity in the first sections of this paper.

Whether or not reflecting these various themes, concerns over energy security, political culture, and economic integration have repeatedly conspired to draw the attention of policy makers to the topic of diversity in the electricity supply industry [496]. As a result, diversity is a high profile energy policy issue in and of itself. For all these reasons, the electricity supply industry offers an ideal practical field in which to test and demonstrate the analytic and heuristic potential of a diversity optimisation procedure based on an

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[490] Having been the field within which such a concept was developed in greatest detail and with greatest subsequent influence (Hughes, 1983). See also: Meier, 1994; Summerton, 1994b; Salsbury, 1994; Coutard, 1994; Rochlin, 1994.

[491] Cf: Munasinghe, 1979; Hirsh, 1989; Thomas and McGowan, 1990; IEA, 1992; Surrey, 1996.

[492] Cf: Summerton and Bradshaw, 1991; Lonnroth, 1993.

[493] As discussed in Section 1.3.

[494] Cf: Keeney, Renn and von Winterfeldt, 1987; Stirling, 1992, 1997; McDaniels, 1994.

integrated multi-criteria diversity index ($\boldsymbol{M}$ or $\boldsymbol{M'}$). Accordingly, this final section of the paper will describe an illustrative application of a diversity optimisation procedure to the issues surrounding technology choice in the UK electricity supply sector.

A schematic outline of a general framework for a diversity optimisation procedure is summarised in Box 22. Before undertaking any act of appraisal, a necessary (but often implicit) starting point must be a decision concerning the perspective under which the analysis is to be conducted and the purpose towards which it is aimed. All analysis requires the establishing of such a frame of reference, and this in turn will depend on a particular array of rationales, interests and values which may be expected to condition the ensuing results. A diversity optimisation procedure is no different in this respect.

For the purposes of discussion, such an exercise might be envisaged in a number of different contexts. It might form part of a relatively narrowly-focused investment appraisal carried out on behalf of a board or an individual executive in a private firm. Alternatively, such a process might form part of an assessment approached from a wider public policy perspective, including attention to regulatory, administrative or political priorities, perhaps in a context such as a local government planning inquiry, a regulatory consultative process, a national government commission or a parliamentary committee hearing. In short, the technique is applicable in principle under any circumstances in which a more orthodox form of appraisal (such as cost-benefit or risk analysis) might be applied. Here (as in the case of a similar exercise conducted by third parties such as unions or non-governmental organisations), a multi-criteria diversity optimisation exercise might be expected to be open to participation by a wide range of stakeholders and other interested and affected parties [497]. Whatever the circumstances, the degree to which all pertinent views are seen to have been taken into account is likely to be a major feature in judging the robustness of the results obtained.

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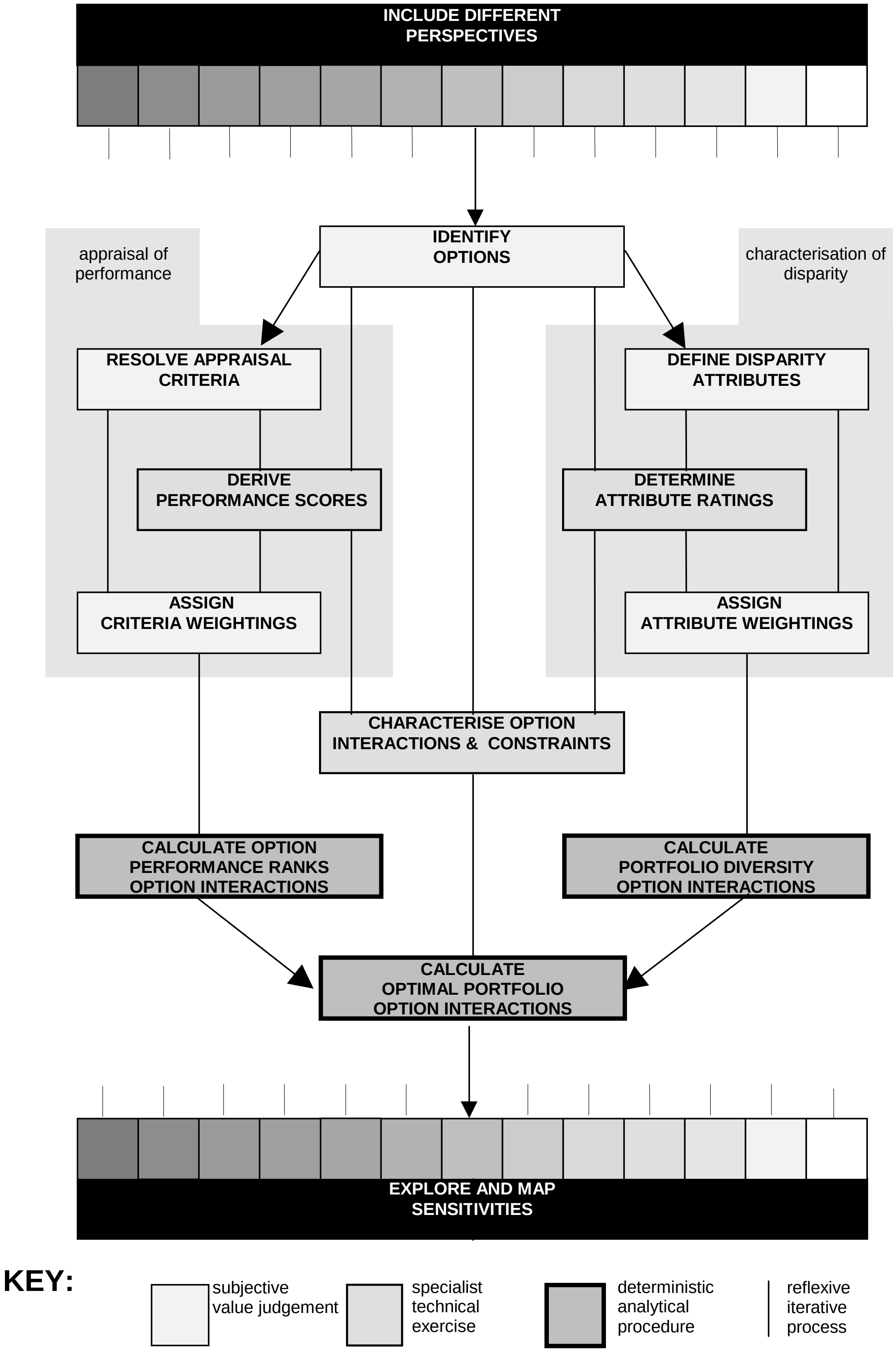
[495] Cf: Stirling, 1994, 1995.

[496] Cf: Stirling, 1996. See also: Llerena and Llerena, 1993.

[497] Joss and Durant, 1995; Renn, Webler and Wiedeman, 1995; Sclove, 1995; Bohmann, 1996; NRC, 1996.

Box 22: Summary of steps involved in a heuristic diversity optimisation procedure



Once a background frame of reference has been established, the first step in a diversity optimisation exercise must be to identify the particular electricity supply options on which analysis will focus. Of course, these need not be exclusively technologically-defined. The history of decision-making in this field suggests that many other factors will influence the definition of contending options, such as the types of primary fuel resources employed, their provenance and associated trade routes, the firms involved in fuel trading and the supply and operation of generating plant, the type of environmental mitigation equipment installed, the trades union composition of the workforce and so on [498]. In reality, the process of option definition will iterate reflexively with consideration of performance under a variety of issues. Here, what is important is that such factors are explicitly considered in the process of defining appraisal criteria and disparity attributes. The particular options identified for the purpose of the present illustrative exercise are listed in Box 23.

The next step is to resolve a set of appraisal criteria under which the relative performance of the different options (and so of the portfolio as a whole) is to be evaluated [499]. It is at this stage that a decision is taken as to whether diversity itself should constitute a criterion in appraisal (which, of course, it need not). Where diversity *is* felt to be of relevance, then a set of attributes must also be identified, representing the factors that are of primary interest in considering the *disparity* of the various options [500]. It should be emphasised again, that, rather than being discrete 'steps' in a linear procedure, the choice of such appraisal criteria and disparity attributes will also be iterative and reflexive in relation to the definition of the options themselves [501]. Once the appraisal criteria and disparity attributes have been defined, they will provide the basis for the scoring of performance, and the rating of key characteristics for each respective option. In order to ensure the avoidance of inadvertent bias introduced though the choice of indicator scales, performance scores must be 'normalised' such as to express their ratios on a comparable scale under each criterion [502]. Expressed

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[498] Stirling, 1994.

[499] As such, the use here of the term 'step' should be taken to allude more to a *dance* than the simple linear progress associated with a *walk* or *run* !

[500] Stirling, 1996.

[501] The process is discussed in more detail in Stirling, 1997.

[502] This is a straightforward procedure set out in many standard texts (eg: Voogd, 1983; Winterfeldt and Edwards, 1986; Nijkamp, Rietveld and Voogd, 1990; Bogetoft and Pruzan, 1991; Janssen, 1994) and in the present context in Stirling, 1997.

simply as ‘high (H), ‘medium’ (M) or ‘low’ (L), schematic performance data are shown for the present set of options and criteria in Box 23 [503].

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[503] The primary sources for this empirical picture are discussed in detail in Stirling, 1994.

Box 23: Illustrative inputs for a diversity optimisation exercise on the UK electricity sector

Inputs for options. criteria, attributes, scores, ratings, weightings, constraints & interactions. Results displayed in Box 21.

OPTIONS	PERFORMANCE CRITERIA					DISPARITY ATTRIBUTES				
	Cost [1]	env [2]	sec [3]	dev [4]	ind [5]	scale[6]	form [7]	tech [8]	pop [9]	sys [10]
weight	high	medium	medium	low	low	high	high	medium	low	low
	score					rating				
coal	medium	low	high	high	medium	large	fossil	steam	medium	no
oil	medium	low	low	low	medium	large	fossil	steam	medium	yes
gas	high	medium	low	medium	high	medium	fossil	aero	high	yes
nuclear	low	low	medium	medium	low	large	nuclear	steam	low	no
wind	medium	high	high	high	high	small	renew.	wind	medium	no
hydro	high	medium	medium	low	high	small	renew.	hydro	medium	no
solar	high	high	high	high	high	small	renew.	PV	high	yes
tide/wave	high	medium	medium	low	low	large	renew.	hydro	high	no
biomass/waste	medium	medium	high	high	high	small	renew.	aero	medium	yes
geothermal	high	medium	high	low	low	small	renew.	steam	medium	yes

OPTIONS	INTERACTIONS [11]									CONSTRAINTS	
	coal	oil	gas	nuc	wind	hyd	solar	td/wv	bio/w	% [12]	
coal										90	
oil	0									90	
gas	+	+								100	
nuclear	0	0	+							75	
wind	0	0	+	–						7	20
hydro	0	0	+	–	–					4	
solar	0	0	+	–	–	–				7	
tide/wave	0	0	+	–	–	–	–			4	
biomass/waste	0	0	+	0	0	0	0	0		12	
geothermal	0	0	+	0	0	0	0	0	0	3	

Notes to Box 23

For purposes of illustration, a set of ordinal categories (low, medium and high) are employed to express weightings, scores and ratings in this exercise. In calculating results, these have been assigned the following numerical ratios: low = 1; medium = 2; high = 4.

1 The ***financial cost to the operator***, quantified in terms of pence per kilowatt-hour (pkWh) and expressed in performance terms as 'high', 'medium' or 'low'.

2 An aggregate indicator of ***environmental performance***, which is itself a multicriteria performance rank relating to weighted sub-criteria such as various forms of atmospheric pollution, land use and nuclear waste, proliferation and accident risks, each assessed under an appropriate physical scale. Performance scores expressed as 'high', 'medium' or 'low'.

3 An index of ***strategic supply security***, again comprising a number of weighted sub-criteria, such as the geographical source of the primary fuel and the vulnerability of supply chains to disruption. Performance scores expressed as 'high', 'medium' or 'low'.

4 A measure of contribution to ***economic development*** objectives including as weighted sub-criteria factors such as employment and regional and rural development. Performance scores expressed as 'high', 'medium' or 'low'.

5 An indicator of ***industrial merit*** subsuming weighted sub-criteria taking account of factors including technological excellence, export potential and national competitive position. Performance scores expressed as 'high', 'medium' or 'low'.

6 The ***industrial scale*** of the generating plant in terms of electric output capacity in MWe. This addresses a number of issues relating to system integration implications. Attribute ratings are expressed as 'large', 'medium' or 'small'. These might be assigned numerical values (respectively) as follows: 1, 0, -1.

7 The ***physical form*** of the primary resource, addresses a number of issues relating to the associated infrastructures and environmental and other policy issues. Attribute ratings are expressed as 'fossil', 'nuclear' or 'renewable'. These might be assigned numerical values (respectively) as follows: 1, 0, -1.

8 The ***technological characteristics*** of the option, addressing issues which tend (to a first approximation) to cluster around the categories: 'steam cycle' (steam), 'combustion turbine' (aero), 'hydroelectric turbine' (hydro), 'wind turbine' (wind) or 'solid state photovoltaics' (PV). These attributes might be assigned numerical values (respectively) as follows: 2,1, 0, -1,-2.

9 The ***political popularity*** of the option captures the general exposure to political opposition in terms of whether it is: 'high', 'medium' or 'low'.

10 A range of ***system considerations*** such as the degree to which an option may be located in areas of the system which are in need of reinforcement. Attributes are categorised: 'yes' or 'no' with corresponding numerical values (respectively) of 1 and 0.

11 The terms in this ***interaction matrix*** are dominated by the issues associated with the integration into an electricity system of numerous small scale intermittent generating units (as with wind turbines) or a few highly inflexible large scale units (as with nuclear reactors). Numerical values may be assigned to the ratings as follows: '–' = $^{2}/_{3}$, 0 = 1,'+' = $^{4}/_{3}$

12 The ***constraints*** displayed here are purely illustrative, relating to factors such as system integration and resource supply curves. As is shown, collective constraints may be applied as readily as individual constraints. In actuality, this particular set of constraints is rather conservative with respect to the renewables, reflecting just the resource available from the best tranches of the various available options. Consideration of less favourable tranches would increase the overall available resource.

Following the discussion at the end of the last section concerning the characterising of discontinuities in the performance curves associated with different options [504], Box 23 also displays an illustrative set of constraints for the different options. In a more detailed exercise, each individual generating option might be divided into a number of 'tranches', each displaying incremental differences in performance under one criterion or another and associated with a specific constraint in terms of the proportional contribution which it may make to a portfolio. For instance, the 'wind power' option defined here effectively represents only the most favourable tranche available to the UK systems, that which is associated with the use of the best sites. Where less favourable sites are to be utilised, further tranches of the wind (and other renewable) options might be included in analysis. These will automatically be treated by the diversity optimisation procedure described in Section 3.3 as if they were different options displaying identical (or virtually identical) disparity [505]. Accordingly, they will automatically be drawn on in sequence of diminishing performance.

Based on the performance scores and disparity attributes determined for the entire range of options, weightings may then be assigned to each performance criterion and disparity attribute. These will reflect the relative priority attached to each criterion or attribute under each of the particular perspectives included in the appraisal. The perspectives of different constituencies and interest groups may quite readily be expressed in terms of different weighting schemes. There are many different possible approaches to the assignment of weightings in multi-criteria evaluation, but the simplest is simply to assess the relative importance attached to a swing from best to worst performance under one criterion, compared to a swing from best to worst performance under another, and repeat this for each criterion. An indicative set of attribute and criteria weightings of this sort is also displayed in Box 23.

The final input to the diversity optimisation procedure is to specify the character of the interactions between options. Depending on the context of the analysis, this may focus on issues such as the connectivity of associated 'techno-economic networks'. On the other hand, it may relate simply to

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[504] Section 3.4.

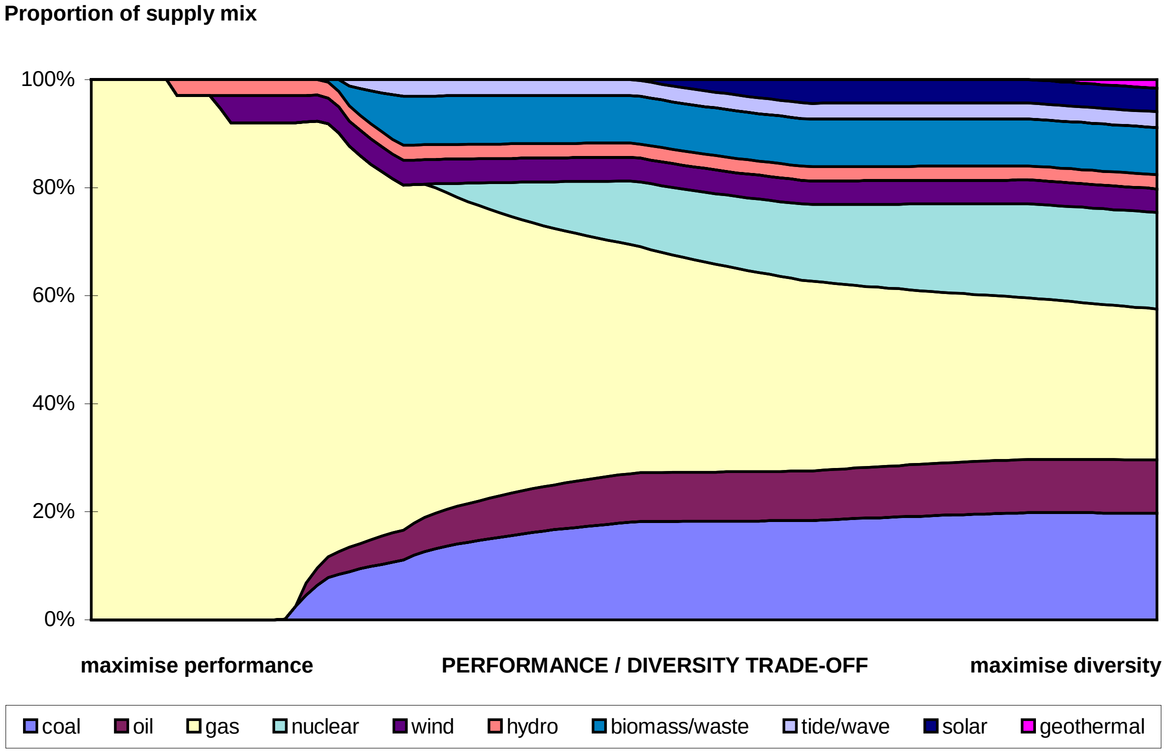
[505] Unless, of course, separate *tranches* also differ in terms of their disparity attributes, but this would effectively make them separate *options.*

operational characteristics of the different options, such as those discussed in the last section (and displayed in Box 21). Either way, each pairwise element in the interaction matrix will constitute a weighting. Values greater than one represent positive synergies serving to enhance the performance of a pair of options. Values less than one represent negative interactions that act to diminish the attractiveness of a pair of options. An indicative set of pairwise interactions for UK electricity supply options is also reproduced in Box 23.

Based on each set of inputs (such as those specified in Box 23), the diversity optimisation exercise will then perform a Monte Carlo procedure. This generates a large set of random portfolios which can then be subjected to Pareto-dominance analysis, resolving optimal trade-offs for the multi-criteria performance of the individual options against the diversity (and interactions) in the portfolio as a whole evaluated under the extended index M' (Equation [11]). The entire procedure is described in more detail in Sections 3.3 and 3.4 of this paper. Those portfolios that lie on the Pareto-efficient frontier are identified analytically, and their composition established. Accordingly, Box 24 displays the composition of the complete range of diversity-optimal portfolios derived by this means for the set of options and associated assumptions described in Box 23.

Box 24: A set of optimal trade-offs between diversity and performance in the UK generating mix

See Box 23 for input assumptions on options. criteria, attributes, scores, ratings, weightings, constraints and interactions.



3.5.2 ‘Pareto-Efficient Frontiers’ and ‘Political Sensitivity Maps’

The chart displayed in Box 24 shows how, under the perspective characterised by the input data in Box 23, the composition of the diversity-optimal UK electricity supply mix will vary with changing assumptions over the relative importance of portfolio diversity, on the one hand, and portfolio performance on the other. Although rather simple in appearance, the resulting picture integrates a range of quite complex factors. It takes account of the performance of the different options (and the constraints on the contributions of their component tranches) under a wide range of criteria, together with the subjective priorities attached to these criteria under one particular perspective. It takes account of the degree to which the various options differ from one another under a range of key disparity attributes. Due to the fundamental structure of the index ***M´*,** Box 24 also takes account of the degree of variety and balance in the portfolio itself. Finally, it takes account of the way that the different options are held to interact with one another on a real electricity system. Yet, despite the complexity associated with such a wide range of divergent factors, the treatment of these issues is relatively transparent and intuitively robust, with all pertinent input variables for all options, criteria and attributes amenable to display on a single page (in Box 23).

The first point to make in relation to Box 24 is that - although efforts have been made to preserve realism for the purposes of exposition - it remains the result of a hypothetical exercise involving a particular (highly stylised) set of input assumptions. In the absence of a concrete policy context for the present exercise, or the empirical grounding of such assumptions in a participatory consultation exercise, no conclusions should be drawn from this *particular* set of results concerning *real* electricity supply strategies in the UK. The purpose of the present exercise is rather to illustrate the *kind* of insights that might be obtained through the application of a diversity optimisation procedure in a practical decision-making context.

Having said this, it is evident from Box 24 that the results of the diversity optimisation performed on the data set in Box 23 are not trivial in character. It *does* seem possible to draw from this exercise a number of quite firm and potentially useful conclusions concerning the analytical and heuristic value of a diversity optimisation procedure such as that described in this paper. In order briefly to outline the type of conclusions that *might* be drawn from such an exercise, the results given in Box 24 may be discussed *as if* they were based on input assumptions and data arising from an exhaustive consultation procedure.

As the eye moves from left to right in Box 24, different options are introduced into the diversity-optimal portfolio in sequence of diminishing overall performance (under the criteria, scores and weightings given in Box 23) tempered by the disparity of the incoming option in relation to the existing composition of the portfolio at that particular trade-off between performance and diversity. As such, the pattern in the introduction of options into the diversity-optimal portfolio is a complex path-dependent process [506]. However, the set of portfolios actually displayed in Box 24 is a minute sub-set of all possible portfolios comprising these options. There are no portfolios, for instance, in which the nuclear contribution is larger than the aggregate renewable contribution. There are no portfolios containing nuclear power which do not also contain the maximum specified contributions (in this exercise) from hydro, wind and biomass power [507]. Even where a relatively high priority is attached to diversity, there appears to be no good reason to introduce significant solar capacity until the capacity available from the best tranches of hydro, wind, biomass and waste have all been exhausted. For this particular set of input assumptions, then, and depending on the preferred trade-off between performance and diversity, it can be concluded that - even where diversity is a major consideration - any new investments in electricity supply might most efficiently be aimed at building up a substantial renewable contribution to the supply mix, rather than in maintaining the nuclear option.

Of course, even were this the result of an analysis conducted on the basis of an empirically-derived set of criteria and attributes with their respective weightings, there would still be the question of the sensitivity of the overall picture to the subjective value judgements embodied in these weightings. Even a single decisive individual will typically experience considerable ambivalence concerning specific trade-offs between

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[506] Under certain conditions an option may enter a portfolio as the diversity weighting is increased and display a sharply rising proportional contribution until the diversity weighting is reached at which another option enters. At this point, the earlier-entering option may then display a rapid decline in proportional contribution until a stable value is reached. The reason for this is the non-linear effects introduced by consideration of the disparity of newly entering options relative to an existing portfolio.

[507] In fact, if further tranches of each of these options had been specified, it seems likely that these also might have been drawn upon in preference to nuclear.

different incommensurable priorities [508]. Value judgements are likely to alter from time to time and from context to context. What is true of an individual is, of course (for the reasons discussed in Section 1.4) even more true of different constituencies in a modern pluralistic industrial society such as that of the UK. In order to be robust in these terms, then, the outputs of a diversity optimisation exercise must systematically explore these wider sensitivities to essentially subjective and political factors. Such an exercise is simulated schematically in Box 25, the final illustration in this paper.

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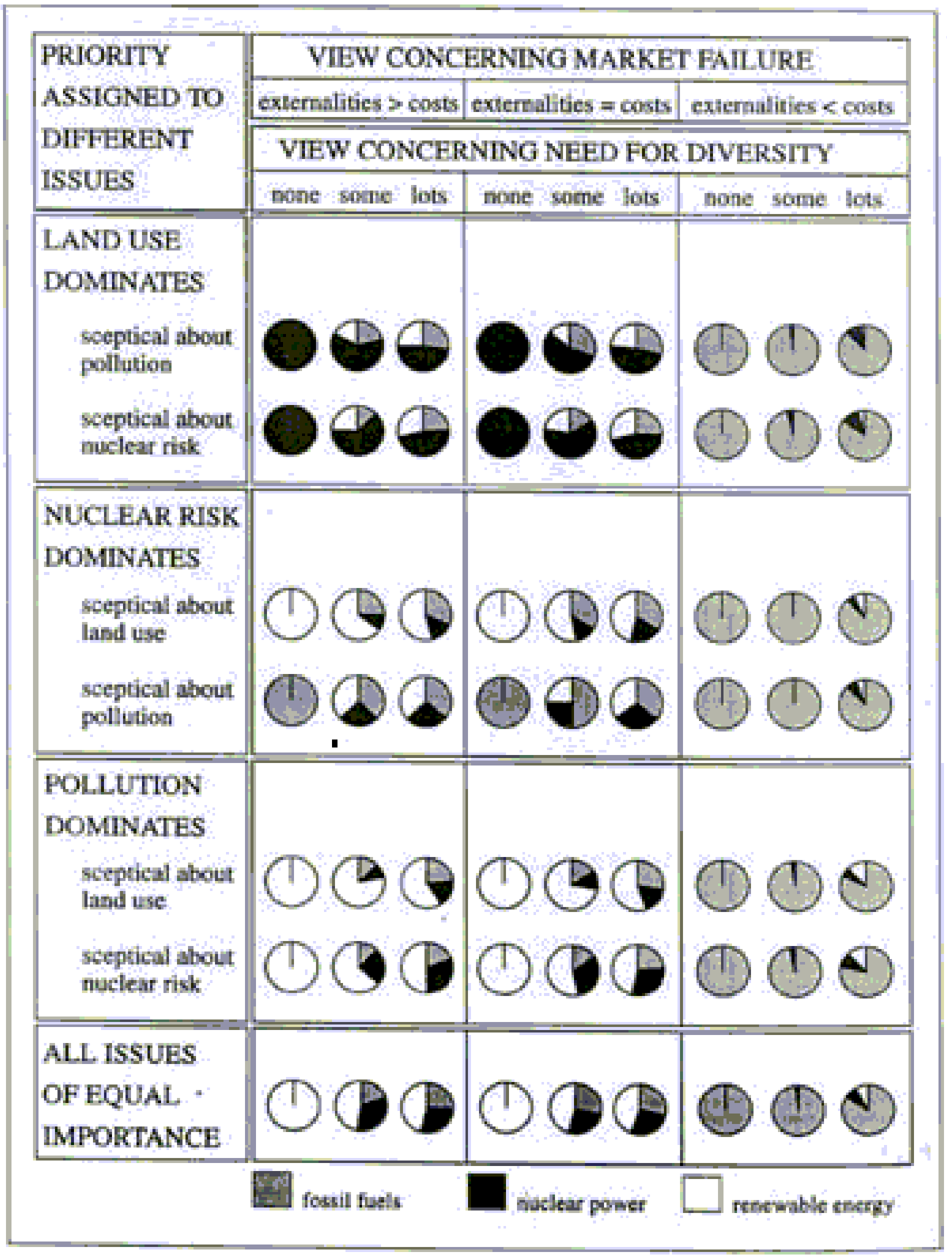
[508] Eg: Fischoff, Slovic and Lichtenstein 1980; Nosofsky, 1992; Gregory and Slovic, 1997; chapters in Foster, 1997.

Box 25: A complete set of optimal diversity / performance trade-offs for the UK generating mix



Box 25 displays the results obtained by diversity optimisation under a symmetrical set of 81 permutations of hypothetical divergent value judgements concerning the relative subjective importance attached to criteria of economic cost, atmospheric pollution, land use, radioactive pollution and portfolio diversity. As such, it might be termed a '***political sensitivity map***', combining scientifically and technically-derived performance assessments with the systematic exploration of divergent socio-political value judgements. The particular set of weightings and performance scores associated with this set of results are discussed in more detail in another paper by the present author [509]. For present purposes, the details do not matter - the aim is simply to illustrate the process. In terms of Box 25, for instance, the results displayed in Box 24 might therefore relate to just three of the permutations displayed - a 'low', 'medium' and 'high' weighting on diversity under a particular set of weightings on other criteria. Again, the efficacy of presenting a diversity-optimisation exercise in terms of political sensitivities is best illustrated if it is imagined that the results displayed in Box 25 *were* grounded empirically on the basis of a formal consultation exercise involving participation by a number of political and cultural constituencies and interest groups, each with different perspectives concerning the issues associated with choice among electricity supply options.

The first point to be made in relation to Box 25 is that, rather than converging to a single precisely defined prescriptive conclusion, this political sensitivity mapping exercise yields a number of apparently highly divergent signals. Far from being a perverse feature of the analysis, this is an indication of the fidelity with which the technique reproduces the degree of discord inherent in the political discourse that it reflects. Each of the different electricity supply options are, under one perspective or another (and where zero weighting is attached to diversity), assigned the entirety of the 'optimal system'. Different perspectives yield a wide variety of conceivable ordinal ranking sequences for the various options. Yet, despite this initial apparent indeterminacy, a number of useful regularities are also evident in this picture. It is on the basis of this type of regularity that a political sensitivity map based on the results of a diversity optimisation exercise might offer a useful contribution to public policy making concerning policy-making or the regulation of investments or technology choice.

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[509] Stirling, 1997.

For instance, to the extent that the deliberate pursuit of diversity is a means to accommodate a plurality of value judgements concerning the relative importance of different factors in appraisal, the evident discrepancies between the optimal supply mixes yielded under different perspectives is itself a compelling indication that some degree of diversity in this area might be a reasonable public policy objective. Beyond this, it is evident that a supply mix dominated by the fossil fuel options is consistent only with a view that environmental issues are together significantly less important than cost issues, or where there is a combination of scepticism about the importance of atmospheric pollution and a perception that there is only a minimal requirement for diversity. In other words, only by adopting perspectives such as these would it be possible to justify continuing to aim for an electricity supply mix on the lines of the present *status quo*.

Where land use issues are held to dominate other environmental concerns (perhaps under some of the more conservative of conservationist perspectives), nuclear power assumes a very high proportion of the supply mix - ameliorated only by the perception of a need for diversity. Under virtually all other circumstances, however, and except where there is scepticism over the importance of atmospheric pollution, the renewable energy options dominate the electricity supply mix [510]. Indeed, in simple numerical terms, the renewables dominate as many of the hypothetical optimal supply mixes as do the fossil fuels. When it is taken into account that the renewable options presently comprise less than 3 % of the UK supply mix, it is clear that under almost every single perspective where any value at all is assigned to diversity, the renewable contribution to the supply mix is substantially greater than at present. Furthermore, under more than one third of those circumstances where diversity is considered unimportant, renewables comprise the entire supply mix. The overall difference between the general prominence of the renewables and that of nuclear power is particularly striking.

On the basis of a set of results such as these, and unless overwhelming weight were given to a minority of perspectives, it would be difficult to justify any regulatory intervention in electricity supply markets which acted to favour nuclear power over the renewables. Where they rely on the transparent display of regularities in a map of *real* subjective perspectives, conclusions such as this would be highly pertinent to decision making. They would be all the more robust and specific, since they are based on the explicit consideration of socio-political sensitivity, rather than on claims to some sort of transcendent objectivity in analysis. When undertaken as part of a multicriteria appraisal, with full expressions of sensitivities, then, a diversity optimisation procedure appears to offer a tool of potentially significant analytic and heuristic value. Such an exercise might be applied to a wide range of contexts involving the contemplation of alternative investment, technology or policy choices, perhaps including problems in transport, food or waste management policy or the prioritisation of funding in research and development. In short, the technique is applicable in principle wherever decision makers are wresting with the implications of innovations and network interactions, strict uncertainty and ignorance, technological ‘channelling’ and ‘lock-in’ and the intractabilities of Arrow’s Impossibility.

In effect, what is displayed in Box 25 is a set of alternative ‘technological trajectories’ in the sense of the evolutionary economic literature reviewed in Section 1.3. Each mix of options reflects a configuration that is economically ‘optimal’ (in the broadest sense), given the best available scientific and technological data, together with a particular set of framing assumptions concerning the relative importance of different appraisal criteria. These ‘conditionally optimal’ portfolios of economic options identified by diversity optimisation do not offer a simple yardstick against which to measure the *status quo*. Instead, they represent a set of ‘moving targets’ towards which investment strategies might - under a particular perspective and at any one point in time - be deliberately configured to aim. Whether the perspectives involved are drawn from the viewpoints of different executives in a private firm or different socio-political constituencies in a plural society, a political sensitivity map of this sort is as far as deterministic analysis can legitimately take a decision. In commercial and public life alike, a final choice among investment, technology or policy options must remain a matter of fundamentally subjective value judgement. The *implications* of different values may be revealed by analysis, but the final decision is most properly *justified* through the institutions and procedures of accountability (professional, in commercial life or democratic, in political life) rather than under the spurious guise of an ‘analytical fix’.

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[510] This is the case, despite the somewhat conservative assumptions adopted in this exercise about their cost (at

CONCLUSIONS

The present paper has shown that diversity is an important theme in modern economics and especially in the economics of technology choice. Diversity is variously argued to be a major factor in the fostering of innovation and growth, an important strategy for hedging against intractable uncertainty and ignorance, the principal means to mitigate the effects of 'lock-in' under increasing returns and a potentially effective response to some fundamental problems of social choice. Accordingly, this paper has sought to make the case that diversity is a potentially important consideration in the economic appraisal of portfolios of investments, technologies and policies. In this light, it seems that the development of a transparent and robust general index of economic diversity may offer a basis for a potentially important heuristic and analytical tool.

Given the manifest prominence of the concept of diversity in economics, it is in many ways surprising that the review of the literature undertaken here finds that notions of economic diversity tend often to be rather incomplete and sometimes ambiguous. Based on concepts drawn from a wide range of other disciplines concerned with the analysis of diversity, it is proposed that there may be some merit in a straightforward qualitative characterisation of diversity in terms of the three necessary but individually insufficient properties of '*variety*, '*balance*' and '*disparity*'.

The properties of a number of different candidate general indices of diversity have been discussed in relation to this formal threefold characterisation of diversity. Approaches based on the concepts of variance and covariance, formal taxonomic analysis and distance metrics have each been examined in turn. Although important insights are gained (especially from work in mathematical ecology, psychology and the economics of biodiversity), it is concluded that there currently exists no single index which fulfils the basic criteria which would be desirable in a *complete*, *transparent*, *parsimonious*, *robust* and *consistent* general quantitative index of diversity for use in economics.

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low system penetrations), their land use characteristics and their diversity benefits (cf: details in Stirling, 1997).

However, when economic diversity is considered in the context of investment, technology or policy appraisal, a novel and relatively straightforward approach is suggested on the basis of insights gained in other fields. Accordingly, an *integrated multi-criteria diversity index* (***M***) has been developed and its key properties described. To a greater extent than any alternative, this index is argued to comply with all the conditions set out for a desirable general quantitative index of diversity for use in economics. In addition, it is proposed that a simple elaboration on this basic index (***M´***) permits account also to be taken of a range of factors relating to complex interactions between options in economic portfolios.

A '*diversity-optimisation*' procedure is then proposed, under which ***M´*** is applied as part of a Pareto-dominance analysis of trade-offs between multi-criteria performance and portfolio diversity. Using a Monte-Carlo technique and matrix optimisation procedures (written by D. Waxman) which can run in real time on proprietary software on an ordinary personal computer, it is argued that ***M´*** offers a potentially fruitful basis for a heuristic and analytical tool for exploring trade-offs between diversity and other aspects of performance in portfolios of investments, technologies and policies.

This working paper closes with a schematic demonstration of the use of a diversity-optimisation procedure employing ***M´*** applied to a problem of investment appraisal in the UK electricity supply industry. It is shown that the results of such an exercise are of potentially significant interest, yielding insights concerning the priorities that might be assigned to investments in different options. The technique constructs for each socio-political perspective, an overall picture of the 'moving target' towards which long term investment decisions might best be directed. Where a series of such 'moving targets' are derived on the basis of input data and framing assumptions grounded in an open participative appraisal process, the results may be described as a '*political sensitivity map*'. This provides a relatively robust and systematic picture of the implications for divergent technological trajectories of changes in inputs and framing assumptions in appraisal. In this way, it may be concluded that a multi-criteria diversity optimisation procedure may warrant further attention as a heuristic and analytic tool which allows intractable issues relating to the fostering of innovation, the hedging of ignorance, the mitigating of lock-in and the accommodation of plural values to be more explicitly addressed in the appraisal of investment, technology and policy options.

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