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an investigation into the concept of technological relatedness**

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**The evolution of corporate technological diversification 1930-90:
an investigation into the concept of technological relatedness**

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Abstract

This paper empirically examines the concept of technological relatedness. Technological relatedness has been referred to by academics within the field of evolutionary economics, as the extent to which technologies rely upon similar underlying scientific or engineering principles. This paper challenges this definition and suggests that the nature of technological relatedness is actually far more complex.

Using US patent data, I examine this notion of technological relatedness and its relationship to diversification. My findings indicate that we need to reconsider our understanding of technological relatedness. We need to expand our comprehension to encompass not just technologies that are related via scientific principles, but also to give further consideration to the type of relatedness that arises through their use in production and in systems generally.

A better understanding of technological relatedness would aid our understanding of many other areas of recent and current research. For example: how multi-technology firms manage the forces of increasing technological breadth and depth; the impact this subsequently has for the relationship between technological and product diversity. Our understanding of current organisational trends such as technological partnering and outsourcing could also be assisted as technological relatedness would highlight where technological complementarities lie between potential partners and their nature. As such, the issue is an important area for further research.

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1. Introduction

Technological relatedness is an important concept. It is the subject of current research in itself (Breschi et al, 1998) and an understanding of the phenomenon would illuminate our research in many other areas: e.g. the nature of technological complexity (von Tunzelmann, 1995), technological diversification (Oskarsson, 1990; Cantwell & Fai, 1997), technological convergence (Gambardella & Torrisi, 1996; Andersen & Walsh, 1998). Technological relatedness could also extend its utility to areas regarding the multi-technology character of the firm (Granstrand & Sjölander, 1990) and firm level organisational aspects (Richardson, 1972; Loasby, 1991, 1998). Despite this, technological relatedness is not well understood. Some take technological relatedness to reflect the ‘knowledge proximity’ between two technological areas in that they rely upon the same/similar underlying scientific or engineering principles (Breschi et al, 1998). However, others have seen it as a cognitive and highly firm specific concept which can only be recognised ex-post (Teece et al., 1994; Granstrand et al., 1997; Cantwell, 1998). The latter views give scope to my belief that the perception of relatedness based on underlying principles is too narrow.

In this paper I empirically investigate the notion of technological relatedness within the context of technological diversification and complexity. I do this by analysing US Patent data at two levels (one more disaggregated than the other) for a selection of large manufacturing firms from various industries. One response to technological complexity, might see firms engaging in *broad* technological diversification (increasing their technological breadth). An alternative response to increased technological complexity is that as each technological area in itself continues to advance at a rapid pace, firms may seek greater technological understanding in a narrower range of these and so engage in *focused* diversification (thereby increasing their depth of understanding of the underlying engineering/scientific area) (von Tunzelmann, 1995).

If we take the concept of technological relatedness as being based upon the sharing of underlying scientific and engineering principles, it would seem intuitively obvious that firms face a trade off between increased technological breadth in a less related manner, versus technological depth through more related diversification. It is likely that industry specific differences arise in this respect. In some industries technologies operate within a system more than in others e.g. those required by automotive versus pharmaceutical companies. However, my results here indicate that no such simple trade-off between the two types of diversity appears. What occurs is that technological relatedness occurs between broadly defined

technologies based on quite different underlying scientific/engineering principles just as much as, if not more that it does between technologies which might otherwise be identified as technologically close on the basis of knowledge proximity. Thus, I conclude that because technological diversification in a related-manner occurs across broadly defined technological areas which are not linked by underlying commonality in scientific/engineering principles, we need to investigate the nature of technological relatedness more closely in future research.

2. Background

The topic of diversification not a new one. Traditional economic literature perceives the benefits of diversification as being lower costs and risk spreading arising from the exploitation of economies of scale and scope by firms. Alfred Chandler (1990) has clearly shown in qualitative terms how many of today's 'modern industrial enterprises' have succeeded through diversification. In the latter part of the nineteen and early twentieth century, firms grew large in size by diversifying across geographic markets and exploiting scale economies. Then, by making a three pronged investment into production, management and marketing, and distribution in order to exploit economies of scope, firms were able to draw upon their assets to diversify across product markets. There is now a wealth of literature discussing diversification across product markets, strategic business units (SBU's), industries and geographically (Rumelt, 1974; Porter, 1985; Pearce, 1983; Chandler, 1990; Markides & Williamson, 1994, 1996).

Within the areas of the resource-based and evolutionary approaches, diversification has still largely focused upon the reasons for, and nature of *product* diversification (Rumelt, 1974; Teece, 1982; Pavitt et al. 1989). In the course of such studies the consideration of the notions of relatedness and coherence (Dosi et al., 1992; Teece et al., 1994; Foss et al. 1995; Langlois, 1995) have arisen. These concepts led to the perception that by diversifying into related product markets or other areas which lie 'close in' to the firms existing profile of competencies and lines of business, firms could grow and also attain economies of scale and scope (Chandler, 1990) in their (technological and other) competencies. In this way, with relatedness lying between complementary competencies, the firm is able to diversify and expand whilst corporate coherence is maintained.

The specific subject of *technological* diversification itself is less mature, even in the evolutionary perspective. Interest in the subject in recent years has been stimulated firstly by the observation that artefacts and processes are becoming more technologically complex over

time (Pavitt et al., 1989; Granstrand & Sjölander, 1990, 1992; Cantwell, 1993; von Tunzelmann & Wang, 1997), secondly that amongst the largest firms, diversity in technological competencies has become broader than across product ranges with some firms even deliberately refocusing and narrowing their product ranges in the late 1980's and early 1990's (Markides, 1995; Granstrand et al., 1997; Pavitt, 1997) and thirdly, technologies that were once quite distinct are being combined together in new ways, and 'fusing' to form new technological areas of their own (Kodama, 1986; 1992).

The subject of corporate technological diversification has been addressed more directly at the firm level by business strategists who have made it a central theme in the literature (Argyres, 1996; Markides, 1995; Markides & Williamson, 1994). However, here technological diversification has been subject to a high degree of managerial discretion. Managers (as opposed to the dictates of the markets) decide which technologies they need to use and in which combinations. Hence, the technological relatedness which arises between the technologies used in firms is generally believed to be only recognisable ex-post (Teece et al., 1994; Granstrand et al., 1997; Cantwell, 1998). Only recently have the ex ante and ex post concepts of relatedness been examined together and even then, only in the context of examining the relationship between technological and product diversification (Piscitello, 1998). Ex-post indicators of technological relatedness seem to be stronger than ex ante ones, but it still does not answer the question of where does technological relatedness really lie?

Whilst common scientific/engineering principles probably encompass much of the relatedness between technologies, there is the possibility that a proportion of the relatedness lies in the manner in which they are used in production. Drawing upon Rumelt's (1974) work on product diversification, the use of common scientific principles as the driver of technological diversification can be seen as analogous to the 'dominant-constrained' or 'related constrained' product diversification strategies that firms adopted. The firm relates the new technology to a dominant or central scientific skill/resource and so is in some sense 'constrained' by this technology. This is an attractive view of technological relatedness. It makes intuitive sense, fits in well with the idea that technological complexity can involve a greater depth of knowledge and is complementary to other widely accepted concepts about technology such as the ever-increasing costs of R&D projects which would motivate technological diversification of this type. It is natural that firms would want to maximise their returns on their investment in a new technology as much as possible even if it means making an additional incremental investment to extend the findings in a new but related direction. On

the other hand, the type of diversification motivated by technological relatedness in production might be seen as akin to Rumelt's 'dominant-linked' or 'related-linked' product diversification strategies. In this manner the technologies are each somehow related to another of the firm's technological competencies, but not always the same technology nor based upon the same scientific principle.

Interestingly, Rumelt (op. cit. pp. 150) found that firms using 'constrained' diversification strategies had better economic performances than others, including those using 'linked' strategies. This would seem likely given the 'amortization advantages' of drawing upon the same skills and strengths, in other words the presence of economies of scale and scope in the use of their technologies. However, Rumelt also found that most firms went from using 'constrained' to 'linked' strategies (ibid. pp.148). This suggests that firms even with respect to product diversification were not overly concerned with the relatively short-term financial benefits 'constrained' strategies could afford them. Given that product markets are more volatile than technological fields, would we not then expect firms to consider technological diversification strategies based on linkages to be more strategically beneficial to their long term development and performance than diversification strategies that were constrained to using the same underlying scientific and engineering principles time and time again, even though with the apparent decreasing returns to R&D, this might seem a lucrative short-term proposition? After all, as Markides & Williamson (1994) argue:

"related diversification lies *not so much* in the exploitation of economies of scope ...but in allowing corporations to more cost efficiently expand their stocks of strategic assets...similarities in the *processes* by which strategic assets are expanded and new strategic assets are created are more important than static similarities between the strategic assets that are the *outcome* of those processes" (ibid., pp.150).

Transposing this into context of this paper, if technologies themselves are regarded as the strategic assets², then the underlying principles rendering them similar are actually less

² Markides & Williamson (1994) are careful to point out that 'strategic assets' differ to 'core' first are assets which underpin a firm's cost or differentiation advantage in a particular market and are imperfectly imitable, imperfectly substitutable and imperfectly tradable, they also tend to be market-specific. Core competencies are the pool of experience, knowledge and systems, etc. that exist elsewhere in the same corporation and can be deployed to reduce the cost or time required either to create a new strategic asset or expand the stock of an existing one (ibid., pp.149-150). However, if we take the meaning of 'technology' to be a broad one which encompasses both tacit knowledge embodied in artefacts and processes as well as to mean codified knowledge, then firm-specific technological resources may be viewed both as strategic assets and

important than other factors including the ways in which they are acquired and generated, or used together at various stages of production and within products. As such, a notion of technological relatedness based primarily upon underlying scientific/engineering principles is a weak one and the concept deserves further attention both for the theoretical development of our understanding of the nature of technology and for practitioners in business who would benefit in understanding where the value in their various technologies as strategic assets lie.

Having outlined the literary background to this current paper, a few words must be devoted to the build up of prior empirical work which have led me to my current position of interest. Previous work by this author (Fai, 1998a) found that over the period 1930-90, the prevalence of technological diversification albeit at a fairly aggregate level³, across selected large corporations or firms was surprisingly more widespread and stronger in effect in the more historical decades of 1930-60 than 1960-90. This was a surprising outcome given the recent discussions of the multi-tech firm, the increasingly complex nature of products and processes and the phenomenon of technological fusion. (Granstrand & Sjölander, 1990; Granstrand et al, 1997; von Tunzelmann, 1995; Kodama, 1986, 1992). Further research showed however, that the outcome was partially attributable to the stronger influence of increases in firm size historically (Fai & Cantwell, 1999) and partially to the fairly aggregate level of analysis for the broadly defined technologies. A more refined classification of the technologies revealed that relatively speaking, a more subtle type of technological diversification had been occurring in the more recent decades compared to that of the historical decades (Fai, 1998b). Bringing these two outcomes together has led me to my current proposition regarding the relationship between firm size and technological relatedness in the process of technological diversification over time:

- technological diversification in more historical decades of the period 1930-90 is associated with increases in firm size but not in a technologically related manner.

competencies. Whilst knowledge about the manner in which technologies are accumulated may be viewed as the competence, and the actual technology that results viewed as a strategic asset, the technology itself may also be seen as a pool of competence which can be drawn upon in combination with others to form another strategic asset such as a hi-tech manufacturing process. This is a view of resources similar to that adopted by Barney (1991) and Peteraf, (1993).

³ Within the database used, which is described in the next section of this paper, technologies can be grouped at various levels of aggregation. The one referred to at this point is the level of the 56 technological sectors. The

- in the more recent decades, technological diversification is associated less with firm size, but occurs in a more technologically related manner.

3. Data

This thesis utilises an accumulated patent stock database drawn from patents registered at the US Patent and Trademark Office. Patent statistics present a potentially very rich source of empirical evidence on questions related to technology (see Schmookler, 1966; Scherer et al., 1959; Pavitt, 1988 and Griliches, 1990). Nevertheless criticism has been levied at patents for capturing a measure of inventions only rather than innovations. However, the learning processes which generate accumulated capability that enables new inventions to be made (and hence patents registered), relies on inputs of both new knowledge and inventions. As long as the pattern of knowledge requirements thus reflects the underlying distribution of technological competence across firms, corporate patents may be used as a proxy for the underlying pattern of technological change, and not merely as a direct measure of inventions (Cantwell & Fai, 1997). Thus, within this paper patents will be taken as a proxy for both inventions and innovations as in Pavitt (1988). However, patents are not only a useful measure of innovative activity they are also a suitable measure for the evolutionary approach for several reasons.

The first of these is that because Nelson and Winter (1982) characterise technological change as an incremental, cumulative, path-dependent process, a longitudinal approach is appropriate. As such, the availability of patents over longer time frames render them as the only suitable indicator of innovation in a longitudinal study, albeit to be used with care.

Secondly, although patents are frequently criticised for their variance in economic impact, most being of only small significance this might work in the favour of patents as a suitable indicator in the evolutionary perspective. Since technological change is an incremental process, patents seem to be a suitable proxy for its measurement by registering the incremental contributions of inventors and innovators to state of the art knowledge. The cumulative nature of technological change is also to some extent, accounted for by the use of accumulated patent stocks rather than flows and additionally, the impact of a radical innovation and its diffusion is substantially ameliorated by the use of large numbers of patents (Cantwell & Barrera, 1999).

more detailed level of aggregation referred to later, is that of 399 technological classes which correspond

A further justification of the use of patents lies with their ability to identify a technology with both a firm and a specific technological area which R&D data simply cannot do. Patents are thus, more useful for representing the specific technological focus of firms and the extent of their competence in various technological areas. The level of detail afforded by patents at the very micro level (to specific technological areas within firms, not just the firms themselves), means that they probably provide the best means of measuring the concepts of accumulated technological capabilities and competencies as shown by the use of patent proxies at the firm level in recent work (Cantwell, 1993; Patel & Pavitt, 1994, 1997; Breschi et al., 1998; Cantwell & Fai, 1997). The use of patents to trace the technological evolution of firms however, is a fairly recent innovation in itself. Previous work concentrated on using patents to consider macro level characteristics at the level of the country or industrial sector (Schmookler, 1966; Soete & Wyatt, 1983; Archibugi & Pianta, 1992; Cantwell, 1993; Patel & Pavitt, 1995).

US patent data provides the most useful basis for international comparisons of technological change (Soete, 1987; Pavitt, 1988) because the US has been the world's largest single market and a country that welcomed and encouraged new ideas and innovation. Thus, it is likely that firms (especially large ones), will register for a patent there after patenting in their home countries. Also, the US Patent and Trademark Office imposes common screening procedures on all patent applications so there is a common standard of comparison and to this extent, some of the variability in the quality of the patents is reduced. The data available in the US also cover a very long period of time.

The patent data upon which this paper is based, is part of a database held at the University of Reading, UK which is itself derived from US Patent Office records⁴. The details of its collection are well documented in the works of Cantwell (Cantwell & Andersen 1996; Cantwell & Fai, 1997; Cantwell & Barrera 1999).

The database is composed of both individual and corporate patents granted in the US between 1890 and 1990. Each one is classified by the year it was granted and allows the identification of to which firm the patent is assigned, the firm's nationality and the type of

closely to the technological classes identified by the US Patent Office.

⁴ Many thanks to Professor John Cantwell for access to this database which he compiled with the assistance of ESRC funding.

technological activity with which it is associated at various levels of aggregation. The measures within this paper are based on accumulated patent stocks over the period 1930-90 using the perpetual inventory method, as in vintage capital models. Straight-line depreciation for the separate contribution of each new item of technological knowledge is allowed for over a thirty year period, this being the normal expected lifetime of the capital in which the knowledge is partially embodied⁵.

The organisation of the database is such that whilst firms may be separated into broadly defined and distinct industrial areas it is recognised that the range of technologies these firms are active in may be far more diverse. Hence, firms for and from the database have been selected in a distinct manner from the way in which the patents received by these firms have been allocated to various technological areas. In essence, there are four broad industrial groupings to which firms/corporate groups have been allocated based on their primary areas of *production*: i) Chemicals [chemicals, pharmaceutical, textiles and clothing, coal and petroleum products (oil)]; ii) Electrical [electrical equipment, office equipment (computing)]; iii) Mechanical [food, drinks, metals, mechanical engineering, paper and paper products, printing and publishing, non-metallic mineral products, professional and scientific instruments, other manufacturing]; and iv) Transport [motor vehicles, aircraft (aerospace), other transport equipment, rubber and plastic products (tyres)]. Collectively these will be referred to as the CEMT industrial groupings (see Figure 1a).

[Figure 1 here]

The organisation of the technologies that firms from any of these four broad industrial groupings may be using, is founded upon the US Patent Office's own classification scheme at the level of the classes. Thus patents registered in the 50,000+ patent sub-classes allocated within the Reading database to one of 399 technological *classes*. These in turn have been subsumed into one of 56 technological *sectors* which have then been allocated to one of five broad technological *fields* - chemical, electrical and electronic, mechanical, transport and

⁵It is stressed that thirty years is the average expected lifetime given that there is a huge variance of capital life expectancy between different items. Furthermore, this length of time was selected as it represents a proxy measure of the life of the underlying technological knowledge and tangible devices with which it is associated, rather than the lifetime of a US patent which is generally recognised to last only 17 years (Griliches, 1990, pp. 1662).

'other' non-industrial areas - CEMTO collectively (see Figure 1b)⁶. Given these various areas of technological activity, it should be stressed that not all the technological sectors or classes are necessarily included in the technological profile of any one industrial grouping of firms. However, most large companies have engaged in at least some development in most of the general spheres of technological activity, irrespective of the industry in which they operate. This is the case both for the relatively mature industries - like petrochemicals in which the obvious need to draw upon organic chemistry is combined with the need to be skilled in electronic technology; and in more modern industries such as the rigid disk drive industry where electronic, mechanical and materials based technologies are all required (Christensen, 1993). Furthermore, the phenomenon of companies operating in technological areas outside of those more typically associated with their industrial field might be expected to become even more commonplace in recent times where technological fusion has been seen to be occurring (Kodama, 1986: 1992).

For this paper, only firms that were active throughout the relevant historical period 1930-1990, were included and the selected firms were required to possess an accumulated stock of at least 225 patents by 1930. For the purposes of analytical continuity, some firms have been consolidated into the relevant historical corporate groups despite subsequent de-mergers or separations: IG Farben/Bayer/BASF/Hoechst, Swiss IG/Ciba/Geigy/Sandoz. Overall 32 firms and corporate groups were selected (see appendix Table A1).

Although US patents are available over long periods, their quantity has changed over time and there is a potential for small number problems to arise in any analysis of the pre-1960's period. In order to reduce such problems, selection criteria were imposed upon the technologies, both at the 56 sector level and the 399 class level. The selected sectors were required to possess an accumulated patent stock of 100 patents or more in 1930 ($pat30 > 100$) see Table 1. From the selected sectors an additional requirement was imposed upon the classes within them – classes had to possess ten or more patents in 1930 to be selected themselves ($pat30 > 10$).

[Table 1 here]

⁶ A full list of the technological fields, sectors and classes is available from the author on request.

The assumption that has been made with respect to the relative degrees of technological relatedness between sectors and classes is that technological classes subsumed into a single technological sector will be more related to one another on the basis of their underlying scientific/engineering principles than to other classes in other technological sectors. Similarly, whilst there is less similarity between the technological sectors themselves (and hence relatedness) relative to the relatedness between the classes within them, there is a degree of commonality between sectors in order for them to be allocated to one of the five broad technological fields. Therefore, when I speak of growing technological relatedness I expect to see firms diversifying into more technological classes within a number of sectors, whilst relatively unrelated diversification I shall assume to take place when diversification occurs due to increase in size effects and in a less related manner across sectors generally.

4. Methodology

Further problems associated with the use of patent statistics as an indicator of technological change may include the presence of inter-industry, inter-sectoral, inter-class or inter-firm differences in the propensity to patent, and intra-firm and intra-sectoral differences in the propensity to patent. Inter-industry differences in patenting propensity are eliminated here because this paper deals with intra-industry comparisons only, although admittedly the industrial groups are defined very broadly, especially the ‘mechanical’ group. It is recognised that inter-sectoral, inter-class or inter-firm differences in the propensity to patent may arise, but these are controlled for here, by the use of the intra-industry Revealed Technological Advantage (RTA) index (Cantwell, 1993; Patel & Pavitt, 1994; Cantwell & Andersen, 1996) – see appendix A1 for details. There still remains the possibility of intra-firm and intra-sectoral differences in the propensity to patent, but it is likely that the respective variances of these two factors are systematically lower than the inter-firm, inter-sectoral and inter-class differences.

Oskarsson (1990) highlights that the notion of diversity is generally referred to as a state, and diversification is the process of increasing diversity over time. This implies that to measure diversification I would need to examine the increasing width of the firm’s technological base over time. However, given that the sectors and classes have been selected to eliminate small number problems potentially arising in the earlier periods of the analysis, this is not possible. Those classes and sectors which were too small to be selected on the basis of the two 1930 criterion, will not be picked up in any period thereafter, no matter how significant they may be

come over the course of time. This is a weakness of this analysis. However, at the level of the individual firm, diversification in this sense will be detected because the individual firm itself may have had no patents in the specific sector or class even though the industry to which it is allocated does. The notion of technological diversification in this paper is therefore quite a specific concept. It refers to when a firm's profile of technological specialisation becomes more evenly spread across the selected sectors/classes over time. In other words, when diversification occurs, the firm's concentration of technological specialisation in favoured sectors/classes is falling whilst that in previously less favoured sectors/classes is rising.

The extent of a firm's technological diversification is measured here with the inverse of the estimated coefficient of variation in the RTA index across all selected technological sectors/classes, expressed as a percentage ratio (1/CV) – see appendix A2 for details. If 1/CV rises over subsequent periods, it indicates that the firm's technological profile has become more diversified and vice versa (Fai & Cantwell, 1999).

To examine the influence of firm size on technological diversification a simple linear regression of the following form was conducted for each firm at decade intervals:

$$1/CV_t = \alpha + \beta \ln(\text{Size})_t + \varepsilon_t^7$$

Where 1/CV is the measure of corporate technological diversity in time t and where size⁸ is measured by the firm's total accumulated patent stock in time t and ε_t is the residual. This regression was conducted for every decade from 1930-1990.

The values of the alpha and beta coefficients generated in each decade were then employed in a 'shift-share' analysis in order to separate the effects of diversification due to relatedness from those associated with increases in firm size. For example, in appendix Table A2 the estimated alpha and beta coefficients (columns 2 & 3) generated for the regression for the year 1930, were employed with the average firm size (column 5) for the year 1940 to estimate what the effect of the actual change in firm size would have had upon the firm's technological diversity in the absence of a relatedness effect. The newly estimated 1/CV values

⁷ I acknowledge that the distribution of 1/CV is not necessarily linear, however having tested for linear, exponential and logarithmic distributions for CV, 1/CV and $\ln(1/CV)$ against $\ln(\text{size})$, the most significant results were presented by the linear regression of 1/CV on $\ln(\text{size})$.

in 1940 (column 9) were compared to the actual average (1/CV) values in 1930 (column 6) to see the extent of diversification that would have been brought about *only* through a growth in size over the decade interval (column 10). This notional change in diversification between two consecutive decades (column 10) was subtracted from the actual change in (1/CV) - (column 8) so that the notional change in diversification attributable to an actual shift in the regression line could be calculated - i.e. diversification effects due to relatedness (column 11).

The signs associated with the two notional change effects indicate whether the size and relatedness effects work in the same or opposite directions. Hence, when the figures in columns 10 and 11 are both positive (or both negative), then the two work in the same direction with respect to technological diversification; when the two have opposing signs, they work in opposite directions to one another. This regression and shift share analysis was conducted at ten year intervals and at the level of both the selected technological sectors and the technological classes, across the firms of each of the four broad industrial groups. The full results are given in appendix Tables A2 and A3.

Taking these empirical results, I examined the proposition given earlier, that changes in size compel diversification across sectors in a less technologically related manner, and changes in relatedness compel diversification across classes in a more focused and related manner. The absolute magnitudes of the size and relatedness effects in each case were compared between Tables A2 and A3 for each decade to discover whether their influence was stronger at the sector or class level. A summary of the possible combination of effects is given in Figure 2.

[Figure 2 here]

It should be clear from Figure 2 that diversification type A refers to when the size effect at the level of the broadly defined sectors, exceeds the effect (size/relatedness) driving the diversification/ concentration at the class level. Type B is when the relatedness effect driving diversification/concentration at the class level, is stronger than either effect affecting the sectors. Similarly C illustrates when the relatedness effect at the broader sector level exceeds either effect at the class level, and D shows when the size effect at the level of the classes exceeds whichever effect is occurring at the broader sector level. Thus, given my propositions

⁸ Since the growth of firm size does not occur in a linear fashion, I have chosen to measure size on a natural

relating historical diversification to a size effect at the broad sector level versus the more recent effects of diversification being associated more with relatedness effects at the class level, I would expect to see a prevalence of type A's across the four industries in the earlier decades, which is later replaced by the growing presence of type B diversification.

5. Results

Table 2 summarises the analysis of appendix Tables A2 and A3 using Figure 2 and shows that my proposition about the more historical proliferation of type A loosely holds for the chemical, electrical/electronic and transport industrial groups, type B applies only to electrical/electronics and then only weakly. The types of change in diversity being experienced by each firm are thus more complex than a simple switch from broad, size-induced changes to focused, relatedness-induced changes in diversity.

[Table 2 here]

Chemical firms have experienced a change from broad, size-induced changes in diversity - type A, towards broad, relatedness-induced changes in diversity - type C. This suggests that relatedness as an effect has been growing in importance across chemical firms and that technological breadth was, and continues to be, important.⁹ The electrical/electronic industrial group was always quite varied experiencing types A, C and D in 1930-40. Over time, relatedness-induced changes in diversity across sectors (C) have become more commonplace across these firms, and size induced changes in diversity at the sector (A) and class level (D) have declined. Again, the importance of relatedness to technological breadth as an effect has risen in prominence in this group.

The mechanical group, in keeping with its heterogeneous nature, experiences all four types of change in diversity in 1930-40 but until 1960-70, types A and C become increasingly popular - changes in diversity across sectors are induced by either size or relatedness effects.

logarithmic scale.

⁹ In their analysis of significant innovations and *SIC sector* groupings, Pavitt et al., (1987). found that large chemical (and electrical/electronic) firms tended to enter into other 3 digit product groups within the innovating firm's principal 2 digit activity, while firms principally in machinery, mechanical engineering and instruments were more specialised in their innovative activities within their principal 3 digit activity (pp. 310). If one draws parallels between their 2 digit and 3 digit SIC groups with the technological fields and technological sectors in this research, then the results here for the chemical and mechanical industrial groupings are analogous to theirs.

However, 1970-80 sees types A and C become less popular as the incidence of changes in diversity across the more focused technological classes increases among mechanical firms. Thus it seems that changes in diversity continued to occur due to both size and relatedness effects, but that in the last decade 1980-90, in particular, more mechanical firms became more concerned with technological depth (class level changes) rather than technological breadth (sector level changes)⁹.

Transport firms experienced changes in diversity of types A, C and D in 1930-40, size induced changes at either the sector or class level dominate though. However, in 1940-50, there is a movement across these firms towards relatedness-induced diversification at technological class level (B). Transport firms then experience yet another switch in 1950-60 towards changes in diversity at the broad sector level being induced by changes in relatedness, yet changes in diversity at the more focused class level being induced by changes in size - exactly the opposite relationship to the one I originally proposed. This remains the situation for the transport group for the remaining decades to 1990.

What is obvious is that changes in technological diversity overtime do not conform to a simple trend for each industrial group. A simple switch from changes in diversity of type A are not simply replaced by type B over time. The true nature of changes in technological diversity are more complex. How might this complexity be explained?

Large firms are able to diversify into new technological sectors as they have the resources to do so however, the rising costs of R&D may also encourage them to diversify within their prior accumulated technological competencies. Given the assumption that the classes within a sector are generally technologically closer to each other than to classes in different technological sectors, one would expect more intra-sector diversification across classes, than inter-sector diversification because: i) this enables the exploitation of economies of scope in the learning processes used to generate competence in one technological sector (for example if they are based on similar scientific or engineering principles or techniques) and ii) the marginal costs of entry into a new class within an existing sector of technological competence are likely to be lower than those of entering an entirely new sector. However, balanced against this is the idea that not all classes within a sector need necessarily be of equal value to the firm. The firm should not be discouraged from entering a distinct new class in a new sector just because it is harder and more costly to do so in terms of the time, resources and learning effort to be committed to building up competence in this new area. When the firm does decide to enter a

new class in a new sector, it seems reasonable to assume that it has done so for dynamic strategic purposes. The firm must have decided that this new area potentially offers rich technological opportunities for its technological development because the firm probably had to bridge a larger technological gap between the new technology and its existing competencies and therefore commit greater amounts of resources towards this activity. Therefore, when the size of a firm increases, it can use its resources either to diversify within sectors (on the economies of scale and scope in technology utilisation argument), or across sectors into areas they perceive as crucial to their technological development and long run survival (perhaps foregoing some of the potential economies afforded by intra-sectoral diversification). The firm will have to consider the position of the fulcrum in this balance carefully.

However, when the firm shrinks it is most likely to reduce its activity in those classes which are less central to the firms technological activities, i.e. are of relatively less value than others. This is most likely to be in sectors where there are large numbers of classes in which the firm is active because if the firm was active only in one class in the sector (when there are numerous classes subsumed within the sector), it would not have entered the sector in the first place unless that single class was of significance given the greater technological distance and the difficulties this entails. The firm will lose intra-sectoral economies across classes and appear to concentrate across within its technological classes, whilst remaining just as diversified across its technological sectors, even when it shrinks in size. Hence, there is a skewness in the relationship between increases in firm size and the apparent effects it has on broad and focused diversification. Positive increases in size will probably affect technological diversity at both the sector and class level, but negative changes or decreases in size will appear to affect diversity more negatively at the level of the technological classes more greatly than at the level of the sectors. This would appear to partially explain the results of the more recent decades.

6. Conclusions

I have outlined in this paper that although there is much interest in various areas within the fields of evolutionary economics and resource-based theory which relate to technological diversity and complexity, very little is understood about the nature of relatedness between technologies. This is important because our understanding of relatedness impacts upon our understanding of these other two phenomena. The notions of relatedness which are used currently are not well defined and are primarily identified as a firm specific issue which can

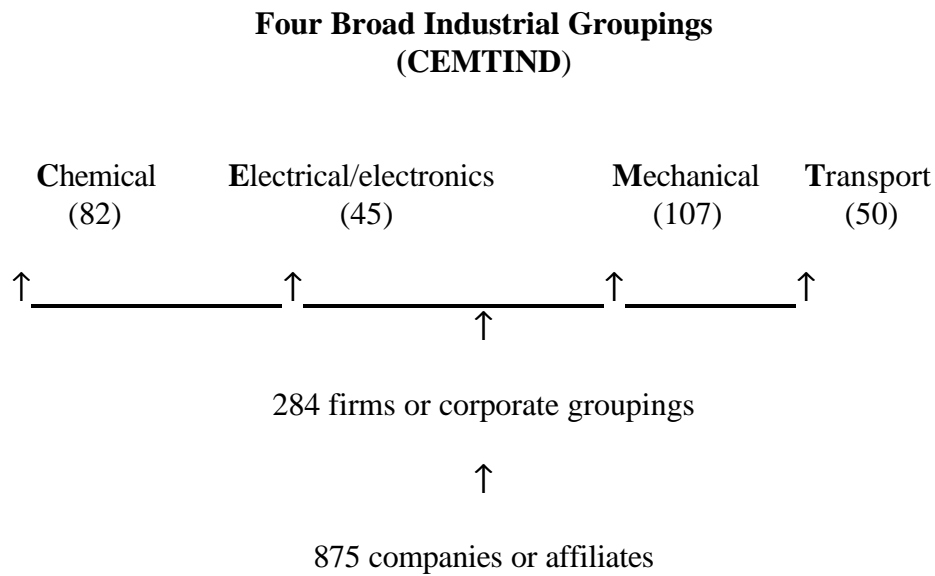
only be scrutinised in more detail though ex-post analysis. A more explicit explanation bases the notion of technological relatedness on the knowledge proximity between technologies, in terms of the underlying scientific/engineering skills encompassed within them. Intuitively this makes a great deal of sense and so starting from this point, the analysis of the influence of relatedness on technological diversification over time was undertaken.

Using patent data, I found in prior work that diversification in recent times has been more influenced by relatedness than increases in firm size, but more interestingly as revealed by this current paper, the latter conception of technological relatedness appeared to be too naïve. Technologies as defined by fairly broad technological sectors seemed to experience greater relatedness than technologies defined by fairly precise and narrow classes. This was surprising given that technological classes were allocated to the broader sectors based upon their apparent closeness in ‘knowledge’ terms. The relatedness between broad technologies apparently quite dis-similar in terms of their underlying principles occurs even in more recent decades where the importance of technological relatedness seems to be greater than in historical times where the overriding concern of the large firms appeared to be growth regardless of whether this was conducted in a related or unrelated fashion. The pervasiveness of this outcome across the selected group of large firms suggests that the concept of technological relatedness need to be re-examined to encompass more than technologies which are proximate in knowledge terms.

It may well be that a notion of relatedness based on scientific/engineering similarity is appropriate to certain industries more than others. However, it seems to me that in all industries, there is scope for relatedness to occur when technologies are used or combined in systems, whether these be production systems, or systems embodied within artefacts themselves. Furthermore, I believe that at least some of these relationships between technologies used in systems, occur with relative frequency perhaps at an industry specific level, and so we can also go beyond the rather loose definition of technological relatedness as a firm specific concept which is left to managerial discretion. As such, I feel that the notion of technological relatedness is ripe for further investigation and research.

Figure 1.

a) *Classification of firms and affiliates to industrial groupings:*



b) *Classification of patent subclasses to technological fields:*

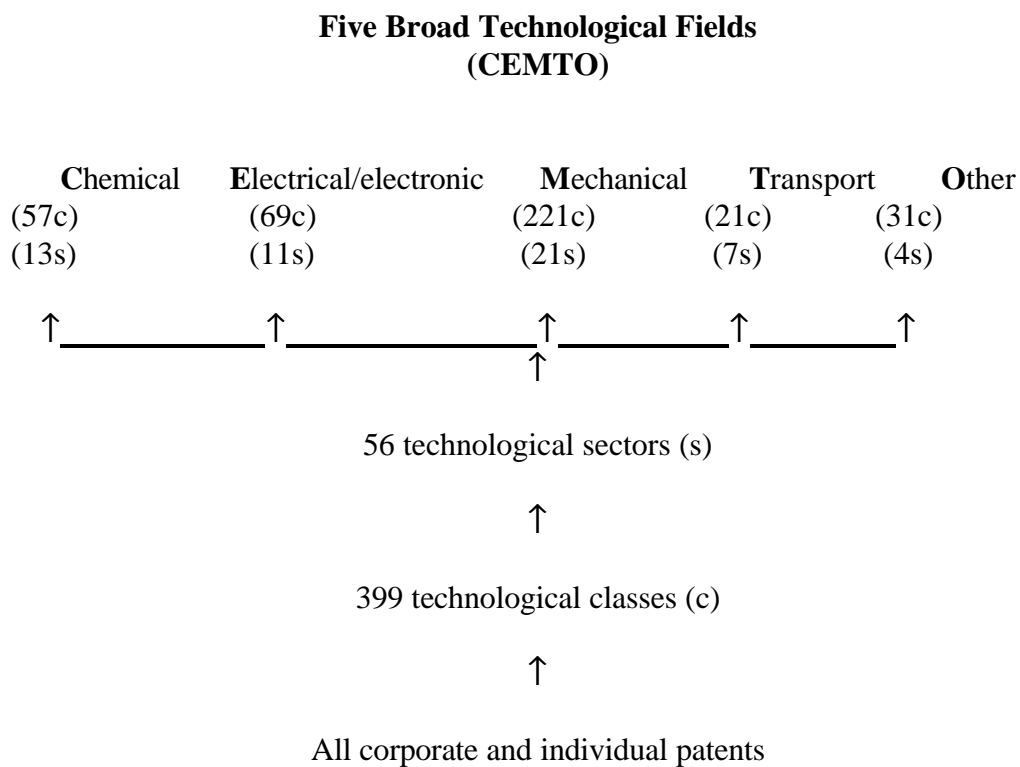


Figure 2 - Types of changes in technological diversity

<p>A</p> <p>Size (56) > Size (399) Size (56) > Relatedness (399)</p>	<p>B</p> <p>Relatedness (399) > Size (56) Relatedness (399) > Relatedness (56)</p>
<p>C</p> <p>Relatedness (56) > Size (399) Relatedness (56) > Relatedness (399)</p>	<p>D</p> <p>Size (399) > Size (56) Size (399) > Relatedness (56)</p>

Which translates simply to:

<p>A</p> <p>Size effect at sector level dominates diversification</p>	<p>B</p> <p>Relatedness effect at class level dominates diversification</p>
<p>C</p> <p>Relatedness effect at sector level dominates diversification</p>	<p>D</p> <p>Size effect at class level dominates diversification</p>

Table 1 - Technological sectors with a patent stock of at least 100 patents in 1930, by industrial grouping

	Technological Sector	Chemical	Electrical	Mechanical	Transport
1	Food and tobacco products				
2	Distillation processes				
3	Inorganic chemicals	X			
4	Agricultural chemicals				
5	Chemical processes	X	X		X
6	Photographic chemistry				
7	Cleaning agents or other compositions	X		X	
8	Disinfecting and preserving				
9	Synthetic resins and fibres	X			X
10	Bleaching and dyeing	X			
11	Other organic compounds	X			
12	Pharmaceuticals and biotechnology	X			
13	Metallurgical processes		X	X	X
14	Miscellaneous metal products		X	X	X
15	Food, drink and tobacco equipment				
16	Chemical and allied equipment	X	X	X	X
17	Metal working equipment		X	X	X
18	Paper making apparatus				
19	Building material processing equipment			X	
20	Assembly and material handling equipment		X	X	
21	Agricultural equipment			X	
22	Other construction and excavating equipment				
23	Mining equipment				
24	Electrical lamp manufacturing				
25	Textile clothing and machinery		X	X	
26	Printing and publishing machinery			X	
27	Woodworking tools and machinery				
28	Other specialised machinery		X	X	X
29	Other general industrial equipment	X	X	X	X
30	Mechanical calculators and typewriters		X		
31	Power plants		X		
32	Nuclear reactors				
33	Telecommunications		X		
34	Other electrical communication systems		X		
35	Special radio systems		X		
36	Image and sound equipment		X		
37	Illumination devices		X		
38	Electrical devices and systems		X	X	
39	Other general electrical equipment	X	X	X	X
40	Semiconductors				
41	Office equipment and data processing systems		X		
42	Internal combustion engines			X	X
43	Motor vehicles				X
44	Aircraft				X
45	Ships and marine propulsion				
46	Railways and railway equipment		X	X	
47	Other transport equipment		X	X	X
48	Textiles, clothing and leather			X	
49	Rubber and plastic products				X
50	Non-metallic mineral products		X	X	
51	Coal and petroleum products	X			
52	Photographic equipment			X	
53	Other instruments and controls		X	X	X
54	Wood products				
55	Explosive compositions and charges				
56	Other manufacturing and non-industrial		X	X	
	TOTAL	11	24	22	15

Table 2 - Diversification types identified for each industrial group

	1930-40	1940-50	1950-60	1960-70	1970-80	1980-90
Chemical	5A 0B 0C 1D	3A 1B 0C 0D	3A 0B 1C 0D	1A 1B 2C 0D	2A 0B 2C 0D	2A 0B 2C 0D
Electrical/ electronic	4A 0B 2C 3D	3A 0B 4C 2D	2A 1B 3C 3D	3A 1B 2C 1D	2A 1B 2C 2D	1A 0B 5C 1D
Mechanical	3A 2B 4C 2D	6A 3B 2C 0D	3A 3B 4C 1D	4A 0B 7C 0D	0A 2B 9C 0D	5A 1B 3C 2D
Transport	2A 0B 2C 2D	1A 2B 1C 2D	0A 0B 4C 2D	0A 1B 3C 2D	0A 1B 2C 3D	1A 0B 3C 2D

Appendices

Notes:

A1

The intra-industry RTA relates a firm's technological advantage in a spectrum of technological activity to that of other firms in the same industry. It shows the firm's (j) share of US patents granted to all companies in the same industrial group, in a sector (i), (or class (k)) relative to the firm's overall share of all US patents assigned to all firms in the industry in question. If P_{ij} denotes the number of US patents granted in sectoral activity i to firm j in a particular industry, the RTA index is defined as:

$$RTA_{ij} = (P_{ij}/\sum_j P_{ij})/(\sum_i P_{ij}/\sum_{ij} P_{ij}) \quad \text{Sector level}$$

Similarly, if P_{ik} denotes the number of US patents granted in class activity k to firm j in a particular industry, the RTA index is defined as:

$$RTA_{kj} = (P_{kj}/\sum_j P_{kj})/(\sum_k P_{kj}/\sum_{kj} P_{kj}) \quad \text{Class level}$$

In both cases, the index varies around unity. Values equal to or above one indicate that relative technological advantage is held by the firm in that particular class/sector compared to other firms in its industry. A value of less than one indicates relative technological disadvantage. In this manner inter-sectoral differences in the propensity to patent are normalised in the numerator of the RTA index, and inter-firm differences are normalised in the denominator.

A2

The extent of a firm's technological specialisation is measured here with the estimated coefficient of variation (CV) in the RTA index across all selected technological sectors/classes.

$$CV_{RTA} = \mathbf{S}_{RTA} / \mathbf{m}_{RTA} * 100\%$$

This takes into account the possibility of a changing mean RTA value in the firm's technological profile over time. This is significant because not all technological sectors are of equal size in terms of their total patent stock. The mean will rise when the firm is specialised in (or moves towards) 'smaller' rather than 'larger' sectors and so must be controlled for when measuring diversification.

The coefficient of variation however, is a positive measure of concentration rather than diversification therefore for ease of exposition, I have chosen to use the inverse of the CV (1/CV) to measure diversification directly.

Appendix Tables:

A1 - List of selected firms by their historical names and compositions in 1930

Chemical

Union Carbide	
Allied Chemical	
Swiss IG	- 1952 , split into Ciba, Geigy, Sandoz; 1960, Ciba-Geigy
Standard Oil (NJ)	merged
Du Pont	
IG Farben	- 1952, split into Bayer, BASF, Hoechst

Electrical/electronic

General Electric	
Westinghouse Electric	
Singer	
Siemens	
AEG-Telefunken	
AT&T	
RCA	
Sperry	- 1986, merged with Burroughs to form
Burroughs	Unisys

Mechanical

US Steel	
Bethlehem Steel	
American Can	
Krupp	
International Harvester	
Deere	
Emhart	
Allis Chalmers	
Vickers	
Eastman Kodak	
Westinghouse Air Brake	

Transport

General Motors	
Bendix	
United Technologies	
Goodyear Tyre & Rubber	
Firestone Tyre & Rubber	
BF Goodrich	

Table A2: Regression and shift-share results - 56 sector level

a) Chemical

year	alpha	beta	rsq	ave size	ave div	chg size	chg l/cv	est ave div	not chg (S)	not chg (R)
1	2	3	4	5	6	7	8	9	10	11
1930	-96.67	31.74	0.34	6.21	100.46			-		
1940	-291.88	55.72	0.71	7.38	119.36	1.17	18.90	137.58	37.12	-18.22
1950	-338.11	59.52	0.74	7.60	114.10	0.22	-5.26	131.44	12.08	-17.34
1960	-129.74	30.77	0.43	7.88	112.58	0.28	-1.52	130.67	16.57	-18.09
1970	-34.57	22.21	0.06	8.37	151.40	0.50	38.83	127.90	15.32	23.51
1980	-912.65	125.19	0.64	8.48	149.57	0.11	-1.83	153.86	2.45	-4.28
1990	-2076.77	264.71	0.95	8.43	153.38	-0.06	3.81	142.11	-7.46	11.27

b) Electrical/electronic

year	alpha	beta	rsq	ave size	ave div	chg size	chg l/cv	est ave div	not chg (S)	not chg (R)
1	2	3	4	5	6	7	8	9	10	11
1930	-131.46	31.63	0.62	6.83	84.67			-		
1940	-153.67	32.47	0.62	7.54	91.04	0.70	6.37	106.91	22.24	-15.87
1950	-100.03	26.45	0.51	7.54	99.51	0.01	8.47	91.26	0.22	8.25
1960	-79.32	24.58	0.43	7.65	108.70	0.11	9.19	102.33	2.82	6.37
1970	-193.90	37.60	0.68	8.10	110.50	0.45	1.80	119.66	10.96	-9.16
1980	-238.25	41.55	0.74	8.36	109.03	0.26	-1.47	120.34	9.84	-11.31
1990	-206.65	38.24	0.66	8.33	111.83	-0.03	2.80	107.79	-1.24	4.04

c) Mechanical

year	alpha	beta	rsq	ave size	ave div	chg size	chg l/cv	est ave div	not chg (S)	not chg (R)
1	2	3	4	5	6	7	8	9	10	11
1930	43.73	1.76	0.01	6.32	54.82			-		
1940	54.26	0.20	0.00	6.55	55.59	0.23	0.76	55.23	0.41	0.36
1950	54.72	0.61	0.00	6.45	58.67	-0.10	3.08	55.57	-0.02	3.10
1960	94.88	-4.54	0.16	6.42	65.76	-0.04	7.09	58.65	-0.02	7.11
1970	89.97	-3.18	0.05	6.67	68.75	0.25	2.99	64.63	-1.13	4.13
1980	114.52	-6.19	0.04	6.91	71.78	0.24	3.03	67.99	-0.77	3.79
1990	178.79	-15.32	0.18	6.76	75.20	-0.15	3.41	72.68	0.90	2.51

d) Transport

year	alpha	beta	rsq	ave size	ave div	chg size	chg l/cv	est ave div	not chg (S)	not chg (R)
1	2	3	4	5	6	7	8	9	10	11
1930	-273.23	58.80	0.70	6.01	80.20			-		
1940	-92.05	28.37	0.58	6.69	97.75	0.68	17.54	120.17	39.96	-22.42
1950	-30.19	20.08	0.20	6.84	107.08	0.15	9.33	101.91	4.17	5.17
1960	-151.73	36.81	0.70	7.23	114.23	0.39	7.15	114.86	7.78	-0.63
1970	-291.07	53.78	0.99	7.54	114.48	0.32	0.25	125.86	11.64	-11.38
1980	-321.28	55.92	0.94	7.68	108.35	0.14	-6.13	122.09	7.61	-13.74
1990	-286.52	51.69	0.80	7.59	105.68	-0.09	-2.67	103.05	-5.30	2.63

Figures in bold are significant at the 5% level

Table A3: Regression and shift share results - 399 class level

a) Chemical

Year	alpha	beta	r-sq	ave size	ave div	chg size	chg 1/cv	est div	not chg(S)	not chg (R)
1930	-125.83	33.56	0.64	6.21	82.64	1.17	12.20	-	39.25	-27.06
1940	-300.80	53.60	0.81	7.38	94.84	0.27	-18.47	121.89	14.37	-32.84
1950	-248.71	43.54	0.63	7.65	76.37	0.23	5.96	109.21	17.85	-11.90
1960	-112.88	26.03	0.43	7.88	82.33	0.50	17.08	94.22	22.77	-5.69
1970	-274.05	45.51	0.52	8.37	99.41	0.11	12.92	105.10	12.71	0.21
1980	-716.08	97.37	0.75	8.48	112.33	-0.06	2.62	112.11	-8.02	10.64
1990	-1205.26	155.73	0.97	8.43	114.94			104.30		

b) Electrical/electronic

Year	alpha	beta	r-sq	ave size	ave div	chg size	chg 1/cv	est div	not chg (S)	not chg (R)
1930	-88.84	23.43	0.39	6.83	71.25	0.70	3.62	-	16.47	-12.85
1940	-32.25	14.21	0.15	7.54	74.87	0.01	2.97	87.73	0.10	2.87
1950	-1.92	10.57	0.11	7.54	77.85	0.11	0.99	74.97	1.13	-0.14
1960	-46.48	16.38	0.29	7.65	78.84	0.45	5.22	78.97	7.30	-2.08
1970	-159.80	30.12	0.73	8.10	84.06	0.26	0.23	86.14	7.88	-7.65
1980	-135.52	26.30	0.68	8.36	84.29	-0.03	1.63	91.94	-0.89	2.52
1990	-127.57	25.65	0.75	8.32	85.92			83.40		

c) Mechanical

Year	alpha	beta	r-sq	ave size	ave div	chg size	chg 1/cv	est div	not chg (S)	not chg (R)
1930	34.03	2.70	0.05	6.32	51.00	0.23	3.06	-	0.70	2.36
1940	54.79	-0.11	0.00	6.55	54.06	-0.13	3.42	51.70	0.01	3.41
1950	46.99	1.63	0.02	6.45	57.48	0.22	0.68	54.07	0.37	0.31
1960	30.98	4.24	0.16	6.42	58.16	0.49	-0.07	57.85	1.12	-1.19
1970	26.44	4.75	0.13	6.67	58.09	0.24	-1.25	59.28	1.14	-2.39
1980	52.22	0.67	0.00	6.91	56.85	-0.15	-0.06	59.23	-0.10	0.04
1990	82.47	-3.80	0.04	6.76	56.79			56.75		

d) Transport

Year	alpha	beta	r-sq	ave size	ave div	chg size	chg 1/cv	est div	not chg (S)	not chg (R)
1930	-261.34	55.02	0.71	6.01	69.41	0.68	9.99	-	37.40	-27.40
1940	-75.94	23.22	0.60	6.69	79.41	0.15	11.12	106.81	3.41	7.71
1950	-56.78	21.54	0.50	6.84	90.52	0.39	2.70	82.81	8.35	-5.65
1960	-166.90	36.00	0.71	7.23	93.22	0.32	7.28	98.87	11.38	-4.11
1970	-206.23	40.67	0.87	7.54	100.50	0.14	-8.66	104.60	5.76	-14.41
1980	-185.69	36.12	0.80	7.68	91.84	-0.09	-6.62	106.26	-3.42	-3.20
1990	-177.84	34.67	0.77	7.59	85.22			88.42		

Figures in bold are significant at 5% level

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