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Investigating the sources of process innovation among UK manufacturing firms

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Although it retains a central position in the main theories of innovation, there are few studies that examine the factors that provide inducements for process innovation at the firm level. Using a large scale survey of UK manufacturing firms, we explore different explanations for why firms develop process innovations. Contrasting the sources of incremental and radical process innovation, our study indicates that there may be complementarities between them. We also find that firm size, the presence of formal research and development, and the use of suppliers as a source of knowledge all increase the chances that a firm will be a process innovator. This article discusses the implications of these results for future theoretical and empirical studies of the innovation process.

1. Introduction

Despite its widely acknowledged economic importance, process innovation has received much less attention than product innovation in the literature on the sources and determinants of technological change. Process innovation, however, remains a central element in the main theories of innovation and economic development, such as the Product Life Cycle (PLC). Process innovation can be defined as new elements introduced into an organization's production or service operations—input materials, task specifications, work and information flow mechanisms, and equipment used to produce a product or render a service—with the aim of achieving lower costs and/or higher product quality (Utterback and Abernathy, 1975; Rosenberg, 1982; Damanpour, 1991; Utterback, 1994; Freeman and Soete, 1997). In this respect, process innovation has often been considered a second-order innovative activity, a rather dull and unchallenging cousin of the more glamorous product innovation. Rosenberg (1982) once described process innovation as the 'grubby and pedestrian' side of the innovation process, involving little of the great events that characterize product innovation.

Notwithstanding the importance of process innovation, there are few studies that empirically investigate the inducements to conduct process innovation at the firm level. Drawing on a sample of 2885 manufacturing firms from the UK innovation survey, we explore the potential relationship between process and product innovations.

We also investigate the impact of external knowledge sources and the effects of innovative activities on process innovation. In addition, we focus on a range of traditional sources of innovative activity, such as research and development (R & D) expenditure. Using the UK innovation survey, we are able to contrast the factors that shape whether firms achieve different degrees of novelty in their process innovations.

Understanding the sources of process innovations is important for at least three reasons. First, process innovations are an important source of increased productivity, and understanding the different factors that cause firms to innovate may lead to greater knowledge about the sources of economic development. Second, process innovation can enable firms to gain competitive advantage; thus, a better understanding of process innovation allows a greater appreciation of the means by which firms gain and sustain competitive advantage. Third, process innovation is an important element in government innovation policy, and exploring the different circumstances that evoke process innovations reveals the mechanisms that support increased private sector innovation.

The article is organized as follows. Section 2 presents empirical and theoretical evidence about process innovation from the literature on the sources of innovation. In section 3, we outline the method, describing the UK innovation survey and the variables used in the statistical model. We also explore the different types of process innovations listed by firms in the survey and the level of process innovation in different industries. In section 4, we present the results; section 5 concludes the article.

2. Theoretical and empirical background

2.1 The role of process innovation in innovation studies

Histories of technical change and innovation have shown that process innovation can profoundly shape patterns of industrial development (Rosenberg, 1982). The paradigmatic example is the use of the assembly line in the production of the Model T Ford. Yet few other process innovations have had a similar impact. Indeed, most process innovations involve small-scale changes in the method of production, often involving fairly routine operational improvements. For example, deployment of a new machine tool that might shape the way materials are handled inside a factory rarely has strategic implications for the firm. Rosenberg suggests that process innovations have been subsumed into treatments of productivity and that many of the process innovations firms make are “silent,” requiring little direct strategic decision-making (Rosenberg, 1982), while Tushman and Rosenkopf (1992) describe process innovation as the “most primitive form of innovation” (p. 313). Yet studies of the relationship between process innovation and productivity have found that the ability of a firm to achieve a process innovation can have a significant impact on its productivity (Vivero, 2002). Process innovations are often associated with the introduction of new machinery, and capital equipment of different vintages (Salter, 1960), and the existence of "learning-by-doing" and "learning-by-using," indicating that as firms become more experienced in the use of capital equipment, they are able to increase their productivity (Hollander, 1965; Cabral and Leiblein, 2001).

Compared to product innovation, it appears that firms have less well-developed process innovation strategies (Pisano, 1997). One reason for this lack of organizational attention to process innovation may be that the concept itself is extremely diffuse and elastic. It encompasses both improvements in manufacturing operations through the use of new machine tools and other pieces of capital equipment and changes in the processes of production and distribution. Some authors maintain that it is necessary to separate technological process innovations from organizational process innovations (Edquist *et al.*, 2001). These authors distinguish between those process innovations that are "technology related" from those that involve "no technological elements" and entail only the coordination of human resources (p. 15). However, this distinction is difficult to sustain in practice as many process innovations involve *both* organizational and technological changes. For example, lean production is a major process innovation, which often involves the use of a wide range of new material-processing technologies as well as new work practices (Womack *et al.*, 1990).[1]

2.2 Types of process innovations

Tushman and Anderson (1990) argued that process innovations are subject to considerable variation in their economic and technological impact. Given their particular characteristics, they may have either competence-enhancing or competence-destroying effects on incumbent firms. In a subsequent work, and building on the work of Dosi (1982), radical process changes have been described as advancing "the price/performance frontier by much more than the existing rate of progress" (Gatignon *et al.*, 2002). Incremental process innovations, in contrast, are "those innovations that improve price/performance at a rate consistent with the current technological trajectory" (Gatignon *et al.*, 2002). In Tushman and Anderson's model of technological discontinuities, however, radical innovations are relatively rare, occurring in some industries only every 30 years. Freeman and Perez (1988), on the other hand, make a distinction between new technological systems, which may involve the creation of new industries through the combination or fusion of a range of technologies, and radical innovations, which may be fairly localized in one particular market segment and may be relatively common. Obviously, the frequency of radical innovations depends on the operational definition used within a particular study.

Within the literature on innovation, there are many competing and often contradictory definitions of radical innovation (Dahlin and Behrens, 2005). In this article,

[1]In our study, we focus on technological process innovations.

we refer to incremental process innovation as a process innovation that is new to the firm but not new to the industry: such innovations will have been introduced in the industry by competitors. The introduction of these innovations may produce radical changes in a firm's manufacturing process but by themselves are not new to their industry.[2] Also, in our study, radical process innovations are those process innovations developed by a firm and those that are also new to the industry. In this respect, radical refers to the degree of newness of an innovation to the industry, whereas incremental refers to innovations that may be imitated from other firms in the industry. Despite the fact that industry managers are generally well informed about their competitors' activities, it is often difficult for them to know whether or not their process innovations are the first to their industry (Bloodgood and Bauerschmidt, 2002). With this caveat, our approach does allow us to separate out the incremental (or imitative) from the radical innovations and therefore to contrast sources of process innovation with different degrees of novelty and uniqueness, throwing new light on the sources of process innovation.

2.3 Empirical studies on the sources of process innovation

Given the diversity in the sources and impact of process innovations, it is surprising that there are few studies on the inducements for firms to be process innovators. Of those that do exist, many are partially and poorly integrated into the wider theoretical literature on the nature of sources of innovation. For example, in industrial economics, a number of studies have attempted to theoretically model the factors that shape the propensity of firms to undertake product and process innovations. Some recent theoretical models suggest that firms will favor product innovation where there is a high level of product differentiation and competition is severe (Weiss, 2003). In contrast, process innovation will be undertaken where products are less differentiated and there is less competition in the industry. Bonanno and Haworth (1998) make this distinction by referring to high- versus low-quality firms, reflecting the choices that firms make about which strategy (in this case which type of innovation) to adopt. Although nested in a traditional equilibrium framework, these models are consistent with the PLC approach of Klepper and others, which stresses the importance of the industrial context in shaping the type and rate of innovation (Abernathy and Townsend, 1975; Klepper, 1997).[3] However, these models do not explore the importance of the various

[2]It is possible to imagine that a number of incremental (or imitative) process innovations may have radical performance implications for the firms that achieve them. One common definition of a radical change is where the performance of the system improves five- or sixfold (Dahlin and Behrens, 2005). Given the nature of our study, however, we are unable to explore the performance implications of process innovation, and therefore, these types of improvements cannot be measured.

[3]They also greatly overlap with Porter's (1985) taxonomy of technology strategies. In this framework, process innovation is often associated with the attempts of firms to achieve cost leadership in their market segment or to focus on cost reductions in the production of existing products.

firm-level inducements for individual firms to introduce process innovations, nor do they specify the relationship between product and process innovations at the firm level. They also provide little guidance for understanding managerial decision-making about different types of innovations, except at the most general level.

There are a few empirical studies that focus more directly on the sources of process innovation at the firm level and the relationship between product and process innovations. A central study here is Kraft's (1990), which uses a simultaneous equation to analyze a cross-section of 56 German metal working firms to explore the interdependence between product and process innovations. Kraft found that while introduction of product innovation drives process innovation, process innovation by itself does not act as a spur to product innovation. However, this study was based on a small, single industry sample and did not control for influential firm-level factors (e.g., the use of external sources of knowledge and/or investments in R & D). In contrast to Kraft, Martinez-Ros (2000) found strong complementarities between product and process innovations in a large cross-section of Spanish manufacturing firms. Indeed, Martinez-Ros found that experience in product innovation encouraged process innovation by 36.2% and that firms which achieved a process innovation were 27.3% more likely to be product innovators.

These empirical findings are consistent with the innovation management research. In looking in depth at process innovation inside firms, Pisano (1997) argued that product and process developments are often interdependent. He found that pharmaceutical firms that invested and developed strategies to encourage process innovation were able to gain competitive advantage. Firms that focused their attention on "learning-before-doing," and considered decisions about how to organize production at the early stages of product development, showed better performance than those firms that left process development to the later stages of the product development process. Along the same lines, Damanpour and Gopalakrishnan's (2001) study of the adoption of product and process innovations by banks found a positive association or "congruence." They suggest that the two types of innovations are mutually supportive and that their simultaneous adoption has the greatest impact on firm performance. This perspective is consistent with Milgrom and Roberts (1995) who state that "if doing more of one thing increases the returns to doing (more of) others" (p. 180), then there are complementarities between these activities.

In an empirical study of the differences and relationship between product and process innovations, Cabagnols and Le Bas (2002) use a large-scale sample of French manufacturing firms to explore the factors that determine the different types of innovations undertaken by innovators. This study uses a wide range of variables to examine these determinants. Cabagnols and Le Bas focus in particular on the sources of relative differences among product innovators, process innovators, and product and process innovations. In terms of process innovation, they found that the use of upstream external sources of knowledge, such as suppliers, is one of the key differentiators of product and process innovators. They also found that firms belonging to highly concentrated industries are more likely to be process innovators than product innovators. The innovation strategies of firms also appear to shape their propensity to be either product or process innovators. Cabagnols and Le Bas found that a strategic focus on product "flexibility" and "quality" was characteristic of process innovators. One drawback to their study is that it focused on innovators only, and Cabagnols and Le Bas (2002) make it clear that they "do not try to predict whether a firm will be an innovator or not." Thus, their study says little about the inducements to become a process innovator and presents a somewhat partial picture of the sources of process innovation by focusing on the comparison between process and product innovators.

In a related study, Baldwin *et al.* (2002) studied the determinants of product and process innovations in a large sample of Canadian manufacturing firms. They found that size, the use of trade secrets, foreign ownership, R & D activity, and the number of competitors in an industry are all important factors in explaining why a firm is a process innovator. This study captures information about both noninnovators and innovators, which helps to correct the "innovators only" bias in Cabagnols and Le Bas' research. However, based on their data, Baldwin and colleagues were unable to make a distinction between different degrees of novelty in process innovation. They also did not explore the relationship between product and process innovations.

Another study on the sources of process innovation was performed by Rouvinen (2002) and explored a wide range of variables at firm and industry levels and examined their influence on whether a firm was a product or process innovator. Overall, this study shows that the sources of process innovation and product innovation differ and that process innovation is associated with firms in industries with low appropriability and high capital intensity. Among the firm-level indicators, the average age of employees was negatively related to process innovation, while use of external sources of knowledge and co-operation with nonacademic partners were correlated with process innovation.

2.4 Explanations of the firm-level process innovation

Within this research context, our aim is to understand the sources of incremental and radical process innovation. Like Kraft, we are particularly interested in the relationship between product and process innovations. Existing research and theory would suggest that there is a general degree of association or complementarity between the different types of innovations, emphasizing the mutual interaction in firm's innovation management practices between product and process developments (Pisano, 1997; Martinez-Ros, 2000; Damanpour and Gopalakrishnan, 2001). Given the comparative paucity of theory and research in this area, however, it is difficult to make strong inferences about the complementarities between degree (incremental/radical) and type (product/process) of innovation. Without a time series of product and process innovators, it is impossible to infer a causal relationship between the two variables. With the current datasets (which are largely cross-sectional), it is only possible to examine whether there are associations between types of innovations.

The role of firm strategies for innovation in shaping whether firms are likely to be process innovators is widely commented upon in the literature. But here, too, as we have described, the evidence is limited. Cost-oriented strategies, focusing on large-scale production of fixed design, are often associated with incremental and radical process innovations. However, as Pisano suggests, there may be an association between the management of product and process innovations, indicating that the characteristics of a firm's product development strategy may bring about process changes within the firm. Pisano (1997) suggests that this relationship might involve a rethinking of the production process as a result of the properties of a new product. Cabagnols and Le Bas (2002) provide some support for this in their finding that managerial strategies associated with product flexibility and quality are associated with process innovation. In order to confirm Pisano's empirical observation, further research is required to determine whether there is a relationship between a firm's product development strategies and process innovation.

Innovators often rely on many different external sources of knowledge. Von Hippel (1988) suggests that process innovators often need to work closely with external suppliers in order to develop new technologies. Indeed, capital goods manufacturers' product innovations may beget process innovations among their customers. Regardless of whether a firm sells its products directly to the retail market, or to other businesses, it is often necessary for firms to work closely with suppliers to understand and utilize the full potential of the new technology. Both Rouvinen (2002) and Cabagnols and Le Bas (2002) find that process innovators are likely to draw on knowledge from upstream sources, such as suppliers. Therefore, it could be expected that knowledge from suppliers will be correlated with firm-level process innovation.

However, the role of other external sources of knowledge on the innovative activities of process innovators is less clear. Customers are often the key source of new product innovations, but their role in process innovation remains indefinite (Von Hippel, 1988). Also, although consultants may play a key role in diffusing new practices across industry and may provide critical inputs to help firms develop new products or processes, it is uncertain whether they are a key source of knowledge for process innovators (MacPherson, 1997). Universities are often an important source of product innovations in emerging technology (Zucker *et al.*, 1998), but their role in process innovation is not known. Although the role of regulation in the innovation process is the subject of ongoing debate (Porter, 1991; Jaffe and Palmer, 1997), the importance of regulation as a source of knowledge innovation has been established (Laursen and Salter, 2006). Process innovation may require firms to master detailed knowledge about health and safety and environment regulations. Regulations can also be linked to the introduction of new processes, as firms must comply with statutory or voluntary guidelines. However, given that there is little or no research in this area, it is not possible to infer a relationship between regulation and process innovation.

A further area of investigation is the link between R & D expenditures and process innovation. Expenditure on R & D may reflect the presence of absorptive capacity and, in the case of process innovation, where firms need to exploit new technologies from other firms in their own processes, the ability to capture knowledge from outside may help firms to become process innovators (Cohen and Levinthal, 1990; Zahra and George, 2002). A central difficulty here is to differentiate between product- and process-related R & D expenditures. Conventional R & D statistics do not make this distinction. Mairesse and Mohnen (2005) found a strong relationship between process innovation and R & D intensity for both high- and low-tech sectors in France, a finding supported by Baldwin *et al.*'s (2002) study, which showed R & D to be correlated with process innovation. In contrast, Rouvinen (2002) found no relationship between firm-level R & D and process innovation. However, in theory and in practice, it can be expected that R & D expenditure will be associated with both incremental and radical process innovations.

One area where a considerable body of research and theory on the inducements to process innovation exists is firm size. Size may provide firms with the resources to purchase and amortize new equipment and therefore to develop new process innovations. The PLC suggests that process innovation becomes the dominant type of innovation in the later stages of the industry life cycle when the market is highly concentrated and/or the returns to process R & D outweigh the returns to product R & D. At this stage, firms will shift their innovative focus toward cost reduction and process innovation (Abernathy and Utterback, 1978; Utterback, 1994; Klepper, 1997). Some studies of process innovation have found a direct relationship between process innovation and size (Kraft, 1990; Martinez-Ros, 2000; Cabagnols and Le Bas, 2002).[4] These findings are consistent with the literature on technology adoption and the role of size in shaping the potential of the firm to adopt a new technology (Stoneman, 2002). These studies suggest that it can be expected that large firms will be more likely to be process innovators and are consistent with the work of Cohen and Klepper (1996a, b).

A final line of inquiry in the research on the determinants of process innovation is the role of capital expenditure or capital intensity. Kraft (1990) found that firms with higher capital intensity were more likely to develop process innovations. Indeed, much capital expenditure goes on the purchase of new technology to reshape internal manufacturing processes. However, it is unclear whether relative levels of capital expenditure by themselves are associated with process innovation. Given the substantial problems involved in measuring the capital stock of manufacturing firms, and the lumpy and uneven patterns of capital investment, it is difficult to develop robust measures of capital intensity (Harcourt and Laing, 1971). Also, the cross-sectional nature of our dataset makes it difficult to deal with this question. However, based on the existing research, it can be expected that high levels of capital investment relative to total sales will be associated with process innovation.

[4]Here, again, Rouvinen's (2002) findings are not consistent with other research, as in this study, size is not significant in explaining process innovation.

To sum up, therefore, based on the existing research and theory we would expect to find a correlation between product and process innovations (conditional on observable variables), indicating that there may be complementarities between the two types of innovations. Process innovators can be expected to be large firms with investment in R & D, which draw on their suppliers for knowledge for innovation. However, the evidential base for these statements is modest and further theoretical and empirical work is required before a more comprehensive picture of the sources of process innovation can be provided.

3. Method

In this section, we describe the sample and the variables used in the analysis and outline the analytical method applied in the *Results section*.

3.1 The sample

The data for the analysis come from the UK innovation survey. The survey was implemented in 2001 and is based on the core Eurostat Community Innovation Survey (CIS) of innovation (Stockdale, 2002; DTI, 2003). The method and the types of questions in CIS are described in the Organisation for Economic Co-operation and Development's (OECD) Oslo Manual (OECD, 1997). CIS data are increasingly being seen as a key data for the study of innovation at firm level in Europe, Canada, and Australia. CIS are often described as "subject-oriented" because they ask firms directly whether they were able to produce an innovation. CIS were widely piloted and tested before implementation, and since their first use in the early 1990s, the questions have been continuously revised. The CIS questionnaire itself draws on previous generations of research on innovation, including the Yale survey and the SPRU innovation database (Pavitt *et al*., 1987; Klevorick *et al*., 1995). It allows investigation of patterns of innovation across a large number of industrial firms. It also enables researchers to explore the relationship between indicators of performance and different innovation strategies. CIS data provide a useful complement to traditional measures of innovation, such as patent statistics (Kaiser, 2002; Mairesse and Mohnen, 2002).

The UK innovation survey comprises 12 pages, including a page of definitions. The sample of respondents was obtained from the Office of National Statistics (ONS). The questionnaire was initially sent to the person designated to provide information on the firm's activities, for example to calculate UK gross domestic product (GDP) and/or R & D expenditure. This person was asked to forward the survey to the department in the firm deemed best able to complete the questionnaire. The survey was administered by the ONS and a help service was provided for respondents (Stockdale, 2002).

The survey defines process innovation as "the use of new or significantly improved technology for production or the supply of goods and services. Purely organizational or managerial changes should not be included" (DTI, 2003). Firms were provided with sample responses from previous UK innovation surveys to help them to answer the question about process innovation. Respondents were also invited to describe their most important process innovations.

The survey was sent in April 2001 to an initial 13,315 enterprise units in the UK, and a supplementary sample of 6287 was sent the survey in November 2001. The second mailing was made to top up the number of regional responses to the survey. The response rate was 41.7% (Stockdale, 2002). The responses were entirely voluntary. The sample was stratified by 12 Standard Industrial Classification (SIC) categories and includes the main industry sectors in the UK economy but excludes public bodies, retailers, and hotels and restaurants. The sample was also stratified by region and by size to reflect the overall demographic characteristics of the UK economy. The response rates for sectors, regions, and size classes were largely consistent with the overall response pattern (Stockdale, 2002). While CIS questionnaire data have been used in a large number of studies (Michie *et al.*, 2002; Tether, 2002; Frenz *et al.*, 2005), we focus on the UK manufacturing sector, drawing a sample of 2885 firms.

3.2 Dependent variables

The dependent variables were derived from two questions in the survey about the nature of process innovation. The first is a general question about whether the firm introduced significantly improved or new-to-the-firm processes between 1998 and 2000. The second question enquires whether the process innovation developed by the firm was new to the industry.[5] Given the format of these two questions, the process innovation variable in the survey can take three different values. The firm may be categorized as having (i) failed to introduce a process innovation, (ii) introduced a process innovation, and (iii) introduced a process innovation new to their industry. By distinguishing between these three levels, we not only capture information about noninnovators and hence correct for the bias found in the Cabagnols and Le Bas (2002), we also are able to differentiate between incremental (or imitative) and radical innovations, extending the Baldwin *et al.*'s (2002) study. In this article, we categorize positive replies to the general question on process innovation as *incremental process innovation* and positive responses to the second question as *radical process innovation*.

In our statistical analysis, we consider the relationship between product and process innovations, exploring whether product and process innovations may be complementary. In this context, product innovation is also considered to be a dependent

[5]The answers to the question "During the three year period 1998–2000, did your enterprise introduce any new or significantly improved processes for producing or supplying products (goods or services) which were new to you firm?" were used to classify whether firms were incremental process innovators. The answers to the question "During the three year period 1998–2000, did your enterprise introduce any new or significantly improved processes for producing or supplying products (goods or services) which were new to your industry" were used to identify firms that were radical innovators.

variable. The survey provided extensive information about product innovation, organized along similar lines to the process innovation variables.

3.3 Explanatory variables

The first group of variables for sources of process innovation is related to the ability of the firm to achieve a product innovation. Firms were asked to indicate the share of total sales for products introduced between 1998 and 2000 that were (i) new to the firm, (ii) significantly improved, and (iii) unchanged or only marginally modified. They were then asked whether they had produced any new or significantly improved products that were also new to the market and to estimate the share of sales from these products as a percentage of total sales. Using these data, three variables expressing the share of sales that can be attributed to *significantly improved* products, to products *new to the firm*, and to products *new to the market* were obtained. These measures indicate whether firms were successful in achieving a product innovation and provide an indication of the economic implications of these innovations for the firm.[6]

To explore innovation strategy, we used the answers to a question in the survey enquiring about the effects of innovation. Firms were asked about the impact of their innovative activities on their enterprise in the period 1998–2000. They were asked to rate the impact, on a four-point scale (none, low, medium, and high), in relation to certain product-oriented, process-oriented, and other effects. Product-oriented effects included "increased range of goods and services," "opened new markets or increased market share," and "improved quality of goods and services." Process-oriented effects included "improved production flexibility," "reduced unit labor costs," "increased capacity," and "reduced materials and/or energy per produced unit." Other effects were related to regulations and standards.

In order to explore the implications of management choice and innovation strategy on the potential for process innovation, we created two variables. The first is related to the *cost focus* of the firm and includes all the responses to the process-oriented effects mentioned above. The second focuses on *product development* strategy and includes all the responses to the product-oriented effects mentioned above. In order to reduce the number of variables in the regression, two independent factors for cost-focus and product development innovation strategies were created using principal component analysis (PCA). These constructs loaded into one factor for "cost" and one for "product development strategy."[7] The product development strategy factor is weaker than the cost factor, and the item "improved quality" loads only partially into the factor.

[6]Alternatively, product innovation could be represented by a three-level categorical variable. The empirical analysis shows that results are robust to this change in the specification (the results of this analysis are available upon request). Given that sales measures provide additional information, we have used them in this article.

[7]Factor loadings are available upon request.

However, the Cronbach Alpha coefficients[8] reveal that both factors may be considered to be measures of a single unidimensional latent construct as both are well above the normally accepted lower limitation of 0.7 (cost-focus alpha of 0.92 and product development alpha of 0.89), indicating that both have a high degree of validity.

It has to be said that the use of an "effects" question as a measure of innovation strategy is extremely problematic. The effects question in the UK innovation survey was designed to capture information about the innovative activities of firms that did not introduce an innovation during the period of the survey. Obviously, asking about the effects of innovative activities implies that firms conduct some innovative activities, and the question relates to the impact of these innovative activities rather than their strategies. Therefore, it is a poor and rather ad hoc proxy for innovation strategy. In fact, in previous innovation surveys, this question enquired about the "objectives" of innovative activities, and this wording is more consistent with our interpretation. However, in CIS 3, the wording was changed to "effects," and in most European countries it was only directed to innovators, while in the UK, it was addressed to all firms. Despite these problems, we decided to include it in order to explore Pisano's statement about the relationship between product development strategies and process innovation, to try to gain some indication of whether a firm's product development activities are associated with process innovation.

In order to investigate the role of external knowledge sources, we used the responses to the question in the UK innovation survey about the importance of knowledge and information for innovation from internal and external sources. The UK innovation survey lists 18 different sources—2 internal and 16 external. Firms were asked to rate on a four-point scale (none, low, medium, and high) the importance of each source. We were interested specifically in the roles of a range of external sources, including "suppliers of equipment, materials, components, and software" for *suppliers*, "clients and customers" for *customers*, "consultants" for *consultants*, and "universities or other higher education institutes" for *universities*. For *standards and regulations*, we used three separate items referring to "technical standards," "health and safety standards, and regulations," and "environmental standards and regulations." To measure the importance of regulations, we simply totaled these items producing a variable ranging from 0 to 9.

We also included a measure of *R & D* activity. The survey asks about expenditure on intra-mural (or internal) R & D. However, given the large number of nonresponses to this question, we converted these figures into a binomial variable to indicate whether the firm engages in R & D. Unfortunately, the survey data do not differentiate between process and product R & D expenditures. The R & D expenditure is self-reported in the survey, and the sales figures are taken from register data.

[8]Strictly speaking, the Cronbach Alpha is not a statistical test, but a measure of consistency. It measures how much given variables can be considered to have the same construct. In other words, it measures the degree of co-variance between a given number of variables (Hair *et al.*, 1998).

Since firm size can influence whether firms develop process innovations, we introduced a *firm size* variable—the logarithm of the number of employees (Cohen, 1995). We also introduced a variable to capture the effect of capital expenditure on process innovation. We called this variable *investment expenditures* and calculated it by dividing capital expenditure in 2000 by turnover for the same year. Both measures are found in CIS dataset.

We also introduced two control variables. The first captures *training expenditures* and is based on the responses to a question in the survey about training expenditures for innovation. It is calculated by dividing total expenditure on training for innovation by total turnover. We also added a variable relating to *innovation co-operation*. Earlier innovation research found a strong relationship between co-operation and innovative performance (Powell *et al.*, 1996; Ahuja, 2000; Cassiman and Veugelers, 2002; Tether, 2002). The CIS questionnaire asks firms to indicate whether they have co-operation arrangements with other enterprises or institutions. We used this question to create a binary 0/1 variable, indicating whether a firm collaborates. Finally, we included 18 industry dummies to control for inter-industry differences.

3.4 Descriptive statistics, estimation, and model specification

Descriptive statistics

We began by conducting three descriptive exercises with the objective of gaining a better understanding of the nature of process innovation. First, we made a detailed classification of the written descriptions of radical process innovations. There were 240 descriptions from a possible total of 265 radical process innovations. Table 1 summarizes the distribution of the written responses across five separate categories and presents some examples. The classification was made by one of the authors and is somewhat arbitrary. However, it does allow for the different features of process innovation to be explored in more detail. Table 1 lists five categories of radical process innovation derived from the written responses. Three examples are given for each category. The categories are introduction of new machinery and equipment, changes in production processes, the use of information and communication technologies (ICTs), new management practices, and other. We make a further distinction in the use of ICT between technologies related to design and those focused on improving communication. As expected, radical process innovation appears fairly heterogeneous, involving introduction of equipment, new management practices, and changes in the production process.

Table 1 also summarizes that almost half of all radical process innovations are related to the introduction of new machinery and equipment. Many organizations cited the adoption of new Computer Numerical Controlled (CNC) and robotic machine tools. The second largest group of radical process innovations was improvements in the process of production, often involving new ways of organizing the production process or new logistics systems. Around 20% of the sample indicated

Table 1 Examples and distribution of radical process innovations

Types of process innovations		
Subtype of process innovation *Examples*	Number of references	Share of total (%)
Introduction of new machinery and equipment	115	47.9
Automatic noodle making machine		
Automatic welding of PVC materials		
Injection molded tunnel lighting systems		
Changes in production processes	47	16.6
Modification to cathode processing techniques		
Introduction of bulk packaging of sleeved products		
Change from batch agglomeration to continuous lower energy densification		
Use of information and communication technologies	36	15.0
Use of information and communication technologies in design	20	8.3
CAD for design of kitchens		
Introduction of three-dimensional modeling for design		
Use of rapid prototype technologies and laser analysis tools		
Use of new communication technologies	16	6.7
Network complaint management software		
E-commerce site for sales and services		
On demand printing—book details are held in electronic format rather than as stock		
New management practices	21	8.8
Introduction of lean production systems		
Changing from production line assembly to a single point assembly mode of operation		
Process improvement plan to reduce process loss through use of statistical process control		
Other	21	8.8
Total	240	100.0

Source: UK innovation survey, 2001.

adoption of new ICT as a radical process innovation. Overall, the ICTs were evenly distributed between design and communication technologies. The last major category of radical process innovation was related to adoption of new management or organizational practices. The most common radical process innovation related to management practice was lean production, which was cited by just under half of the respondents in this category. These new management practices were often associated with changes in production processes. For example, the adoption of lean production led to smaller inventories and/or automatic material-handing technologies.

To probe industry levels of process and product innovations, we divided the sample into 18 different industry groups and compared levels of product innovation and process innovation at the industry level. The idea behind this comes from the work of Evangelista (1999) and Pisano (1997). For example, Evangelista creates similar visualizations, comparing, among other things, share of process innovations in a given industry to share of R & D expenditure. Pisano suggests that radical process and product innovations may be related and that it is possible to put different industries in a 2-by-2 matrix with the radical nature of process innovation on one axis and the radical nature of product innovation on the other. We attempted a similar exercise by first comparing the share of process innovators and product innovators and, second, comparing the share of radical process innovators with the share of radical product innovators. In both cases, the shares were calculated relative to total manufacturing. The industries are then displayed as a scatter plot, which indicates the relative positioning of the industries graphically.

Figures 1 and 2 depict the differences across 18 industries in incremental and radical innovation activities, respectively. As the shares of innovators are relative to the corresponding shares of total manufacturing, the lines going through 1 on the x-axis and through 1 on the y-axis represent the level of total manufacturing. A 45° (truncated) line has been added, which illustrates the points at which the share of process

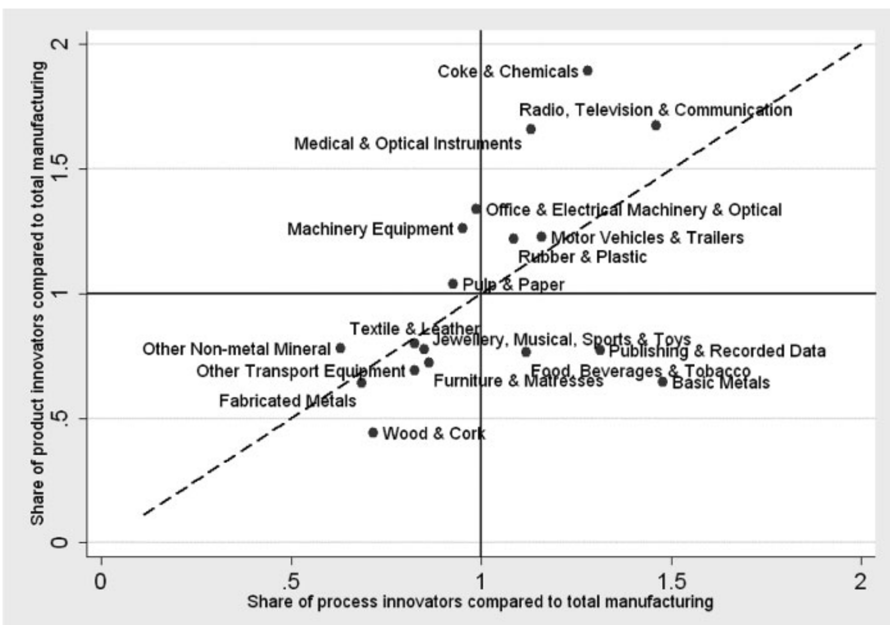

Figure 1 Positioning of industries based on share of innovators in total manufacturing (Pearson's correlation coefficient, 0.5119; $P = 0.0299$).

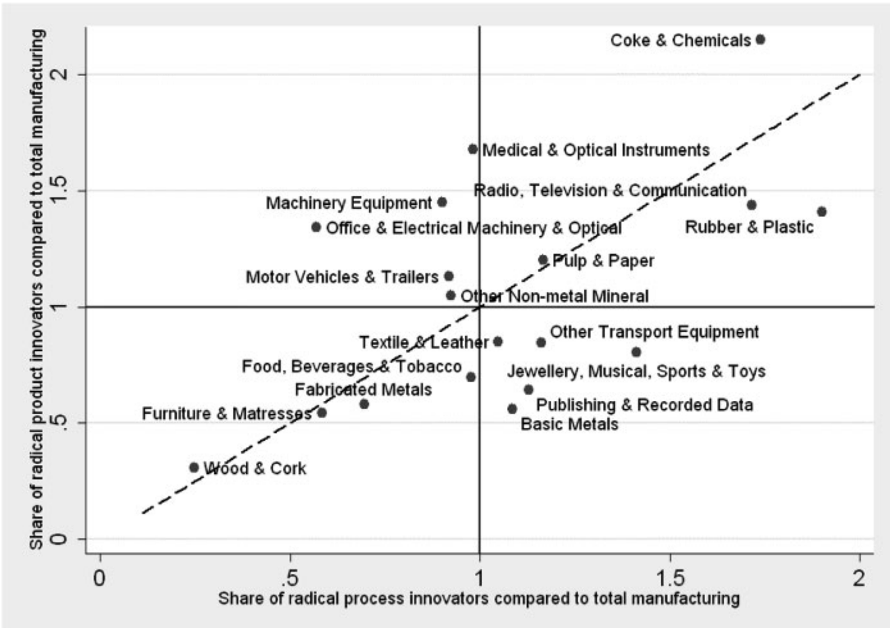

Figure 2 Positioning industries according to the share of radical innovators in total manufacturing (Pearson's correlation coefficient, 0.5657; $P = 0.0144$).

innovators is the same as the share of product innovators. From Figures 1 and 2, it can be seen that the industries with the highest levels of process innovation tend also to have the highest levels of product innovation. Overall, the results are consistent with Pisano's (1997) matrix. However, we found that there are several industries—such as basic metals, and printing and publishing—that show high rates of process innovation and low rates of product innovation but that there are very few industries with high rates of product innovation and low rates of process innovation. We found a significant positive correlation between the relative shares of product and process innovations across industries ($P = 0.0299$). One interpretation of this result is that in industries with high levels of technological opportunity, there are greater opportunities for the development of both new products and processes. As expected, in comparing the two plots, there appears to be a higher level of dispersion in industrial levels for radical process and product innovations (as represented in Figure 2).

Lastly, we summarize the variables used in the regression analysis, including their correlation coefficients. Table 2 reports the basic statistics of and correlations between the explanatory variables used in the regression analysis. The R & D dummy variable has a median at 0, which of course is due to the fact that the majority of the sample does not engage in formal R & D activities. Also, it seems that most firms did not achieve either product or process innovation over the period studied. The correlation

Table 2 Descriptive statistics and Pearson's correlation coefficients ($N = 2885$)

Variables	Mean	Median	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sales attributable to products that are																		
1. New to the market	2.24	0.00	9.76															
2. New to the firm	4.05	0.00	11.98	**0.38**														
3. Significantly improved	4.27	0.00	12.37	**0.33**	**0.24**													
4. Cost factor	0.03	–0.52	0.97	**0.13**	**0.22**	**0.22**												
5. Product factor	0.03	–0.16	0.95	**0.23**	**0.35**	**0.33**	**0.66**											
6. Suppliers	1.12	1.00	1.09	**0.11**	**0.19**	**0.20**	**0.56**	**0.53**										
7. Clients and customers	1.08	1.00	1.09	**0.17**	**0.22**	**0.26**	**0.47**	**0.58**	**0.62**									
8. Consultants	0.49	0.00	0.79	**0.08**	**0.15**	**0.16**	**0.38**	**0.42**	**0.43**	**0.45**								
9. Universities	0.34	0.00	0.69	**0.10**	**0.12**	**0.14**	**0.30**	**0.33**	**0.33**	**0.38**	**0.42**							
10. Standards and regulations	2.81	3.00	2.91	**0.12**	**0.17**	**0.15**	**0.50**	**0.52**	**0.60**	**0.63**	**0.47**	**0.40**						
11. R & D intensity	0.17	0.00	0.37	**0.17**	**0.17**	**0.23**	**0.22**	**0.36**	**0.25**	**0.29**	**0.25**	**0.29**	**0.27**					
12. Log (size)	4.12	3.91	1.41	**0.05**	**0.07**	**0.13**	**0.25**	**0.24**	**0.23**	**0.22**	**0.25**	**0.27**	**0.27**	**0.20**				
13. Investment ratio	0.08	0.02	0.60	0.02	**0.07**	0.03	0.02	0.02	0.02	0.03	0.01	0.01	**0.04**	0.02	0.02			
14. Training expenditure	0.00	0.00	0.11	0.00	0.01	0.02	0.03	0.03	0.03	0.04	0.02	–0.01	0.02	–0.01	0.03	0.00		
15. Collaboration	0.14	0.00	0.35	**0.12**	**0.15**	**0.22**	**0.22**	**0.30**	**0.23**	**0.28**	**0.20**	**0.35**	**0.25**	**0.29**	**0.22**	0.01	0.02	
16. Process innovation	0.35	0.00	0.63	**0.25**	**0.24**	**0.26**	**0.50**	**0.40**	**0.37**	**0.25**	**0.20**	**0.20**	**0.27**	**0.22**	**0.22**	0.03	0.01	**0.28**

Data in bold represent those that are significant at a 5% level.

Source: Own calculations on UK Community Innovation Survey data provided by the DTI.

matrix indicates that R & D activity is positively correlated with both types of innovation variables, supporting the widely held view that R & D is positively associated with innovative activity. As might be expected, it also appears that product and process innovations are correlated at firm level.

Regression analysis

As previously noted, the dependent variable is a categorical response variable with multiple levels. The levels of the target variables (not process innovative, incremental process innovation, and radical process innovation) have no natural ordering in that the numerical values of the dependent variable are arbitrary. We consequently looked at process innovation using a multinomial (polytomous) logistic regression model (Simonoff, 2003). The comparison category of the dependent variable (baseline category) was set to "not process innovative." Accordingly, the regression calculates two parameters for each explanatory variable of which the first (β_{i1}) describes how the explanatory variable (X_i) influences the probability of being an incremental innovator compared to the baseline category (not being innovative). The second parameter estimate (β_{i2}) expresses the effect X_i has on the probability of the firm being a radical innovator compared to not being innovative. A positive β_{i1} suggests a higher X_i is associated with a higher probability of being an incremental innovator. The same holds true for β_{i2} with respect to the probability of being a radical innovator.

The multinomial regression method used and described above only performs two of the possible three comparisons. Therefore, in order to compare incremental and radical process innovators, we applied the Wald test to see whether β_{i1} and β_{i2} are significantly different from each other.[9] This test was applied to each of the explanatory variables.

We report two regressions: the first includes all variables and the second excludes the three explanatory variables measuring product innovation. We followed this strategy in order to gain a better understanding of the independent explanatory power of our explanatory variables beyond their relationship with product innovation.[10]

Complementarities

There are several econometric tests for complementarities. Using the simultaneous equation system method proposed by Athey and Sterns (1998) provides the most consistent estimates of complementarity. However, this approach requires the use of a third dependent variable to examine whether the two types of innovations jointly shape performance, and since we were unable to identify a meaningful third performance

[9]See Hosmer and Lemeshow (2000) for a discussion of the Wald test and its application to multinomial logistic regression analysis.

[10]We also tried to introduce the independent variables in a step-by-step approach. This changed the significance for some variables. Overall, the results of the regression were robust to the different treatments of the introduction of the independent variables; we decided not to include the results of these regressions in this article, but they are available on request.

variable, we investigated the complementarities between process and product innovations by applying the method discussed by Arora and Gambardella (1990) and Arora (1996). One advantage of this approach is that it does not make assumptions about the measurability of the variables in question; it suggests that if a positive co-variation exists between two variables after accounting for a set of common control factors, it may indicate the presence of complementarities. Applying this approach allows us to test whether the correlation among types of innovations is positive, conditional on the observable variables. In order to conduct the analysis, we extracted the residuals from the model without the product innovation variables.[11] The multinomial logistic regression model is submitted with the dependent process innovation substituted for by the corresponding three levels of product innovation and the residuals extracted from the regression. The second step involved estimating the correlation between the residuals extracted from the two regressions. Because we are operating with three variables for product innovation, each regression provided two residuals for incremental innovation and radical innovation respectively. This approach produced six combinations and six correlation estimates. It should be noted that this approach is incomplete and, without a third independent dependent variable, we are unable to directly confirm the existence of complementarities. There may be some unobserved heterogeneity producing the observed correlation. In other words, the correlation between the residuals may be caused by omitted factors, which are themselves correlated with both process and product innovations.

4. Results

4.1 Regression analysis

Table 3 summarizes the regression results for the two models. However, there are some differences between the two models as the inclusion of the product innovation variables changes their global statistics. Both regression models may be regarded as having very little chance of having all zero parameter estimates expressed by the likelihood ratios. The pseudo R^2 changes from 0.26 to 0.29 when the additional variables are introduced. The variance inflation factors (VIFs) indicate that there are no serious multicollinearity problems. Model 1, containing all explanatory variables, exhibits the highest VIF value at 2.51.

Model 1 suggests that the higher share of sales from any type of product innovation increases the likelihood that a given firm will be either an incremental or a radical process innovator. The results also suggest that the first parameter estimate of the share of sales from products new to the market is significantly lower than the second. This suggests that the radical process innovators are positioned significantly farther out on the right tail of the distribution of share of sales from products new to the market, than the incremental

[11]We used a model without the product innovation variables for process innovation because we wanted to explore the existence of complementarities between product and process innovations.

Table 3 Determinants of process innovation, results of multinomial logistic regression

Variables	Model 1		
	Incremental versus not innovative	Radical versus not innovative	Wald test
Share of sales from products			
New to the market	0.0176**	0.0407***	+
	(0.01)	(0.01)	
New to the firm	0.0140***	0.0115*	
	(0.00)	(0.01)	
Significantly improved	0.0111***	0.0196***	
	(0.00)	(0.01)	
Cost factor	0.9718***	1.2478***	+
	(0.08)	(0.11)	
Product factor	0.1467*	0.2774**	
	(0.09)	(0.12)	
Suppliers	0.5936***	0.4641***	
	(0.07)	(0.09)	
Customers	–0.1708**	–0.3203***	
	(0.07)	(0.10)	
Consultants	–0.2262***	–0.0744	
	(0.08)	(0.10)	
Universities	–0.0195	–0.0168	
	(0.09)	(0.11)	
Standards and regulations	–0.0277	–0.0329	
	(0.03)	(0.04)	
R & D	0.2633*	0.3905**	
	(0.15)	(0.19)	
Log (size)	0.1587***	0.2386***	
	(0.05)	(0.06)	
Investment expenditure/sales	0.0375	0.0111	
	(0.10)	(0.14)	
Training expenditure/sales	–0.0646	–0.2899	
	(0.38)	(0.83)	
Collaboration	0.6727***	1.2134***	+
	(0.16)	(0.19)	
Intercept	–2.8369***	–4.3807***	
	(0.32)	(0.45)	
Industry dummies		Yes	
Observations		2885	
Likelihood ratio		–1517.1	
Pseudo R^2		0.29	
Maximum variance inflation factor		2.51	

Table 3 Continued

Variables	Model 2		
	Incremental versus not innovative	Radical versus not innovative	Wald test
Share of sales from products			
New to the market			
New to the firm			
Significantly improved			
Cost factor	0.9419***	1.1640***	+
	(0.08)	(0.10)	
Product factor	0.2754***	0.4808***	+
	(0.08)	(0.11)	
Suppliers	0.5801***	0.4202***	
	(0.07)	(0.09)	
Customers	–0.1354*	–0.2399***	
	(0.07)	(0.09)	
Consultants	–0.2339***	–0.0988	
	(0.08)	(0.10)	
Universities	–0.0285	–0.0385	
	(0.09)	(0.11)	
Standards and regulations	–0.0366	–0.0443	
	(0.03)	(0.04)	
R & D	0.3462**	0.5787***	
	(0.15)	(0.18)	
Log (size)	0.1552***	0.2179***	
	(0.05)	(0.06)	
Investment expenditure/sales	0.0698	0.0722	
	(0.09)	(0.11)	
Training expenditure/sales	–0.0577	–0.3215	
	(0.38)	(0.86)	
Collaboration	0.7189***	1.2447***	+
	(0.16)	(0.19)	
Intercept	–2.7715***	–4.1819***	
	(0.31)	(0.44)	

Table 3 Continued

Variables	Model 2		
	Incremental versus not innovative	Radical versus not innovative	Wald test
Industry dummies		Yes	
Observations		2885	
Likelihood ratio		−1565.7	
Pseudo R^2		0.26	
Maximum variance inflation factor		2.33	

Data inside parenthesis are the corresponding standard errors.

* $P < 0.1$.

** $P < 0.05$.

*** $P < 0.01$.

+/− indicates the parameter estimate on radical innovation is significantly higher/lower than the corresponding parameter estimate of incremental innovation.

Source: Own calculations on UK Community Innovation Survey data provided by the DTI.

process innovators. Not only does process innovation seem to be associated with firms with a higher share of sales from products new to the market but the degree of novelty in the process innovation also seems to have a positive association with the share of firm sales from products new to the market. This indicates that radical product innovation is associated with radical process innovation (an issue that is examined in the next section).

As might be expected, the regression analysis indicates that a cost-focus strategy is associated with process innovation. This supports the idea that firms with cost-focused innovative activities tend to be process innovators. Again, it is important to note that the parameter estimate is significantly higher for radical process innovation than for incremental process innovation. Rather surprisingly, we also found evidence to support the idea that product development strategies are associated with process innovation. The explanatory power of product development strategy, however, declines when we include the product innovation variables. This suggests that the ability to be a product innovator explains most of the variation. By including the product innovation variables, we also absorb the significant difference between the two parameter estimates of the product development strategy variable. Ultimately, however, in terms of product development strategy, the probability of being an incremental process innovator does not differ significantly from the probability of being a radical process innovator. We do find evidence that a product development strategy, regardless of whether a firm is a product innovator, increases the likelihood that a firm will be a process innovator. This finding supports the findings of Pisano and others who link product development strategies to process innovation.

The results also support the idea that using suppliers as a source of knowledge and information for innovation is associated with being a process innovator. This finding is consistent with the existing research and theory and highlights the importance of suppliers in introducing new process innovations into the economic system. However, we found that using customers as a source of knowledge, and using consultants as an external knowledge source, decreases the probability of being a process innovator. These estimation results do not necessarily mean that information from customers/consultants reduces the ability of or incentives for firms to be process innovators. Unobserved firm characteristics are likely drivers of these counter-intuitive results. Drawing knowledge for innovation from regulations and standards appears to have no impact on the chances that a firm will be an incremental or a radical process innovator. In general, the results suggest that process innovators adopt narrower search strategies than do product innovators (Laursen and Salter, 2006).

The presence of R & D in a firm is associated with process innovation. However, when product innovation variables are included in the regression, this decreases the significance of the R & D variable. This indicates that R & D could be seen as a proxy variable for the existence of product innovation capability. Despite this, the results suggest that R & D has some independent explanatory power for process innovation and that the presence of R & D activities indicates that firms have some degree of absorptive capacity. However, more refined treatments of the relationship between R & D and process innovation would be required to fully understand how R & D shapes the ability to achieve process innovation and how different types of R & D influence it.

As could be predicted based on other studies, we find that firm size is significant in explaining process innovation in all models. In this respect, our findings are consistent with the research on technology diffusion and adoption (Stoneman, 2002). It indicates that firms with considerable resources are likely to be able to develop new processes, which small firms, operating within greater resource constraints, may be unable or unwilling to develop. These results also lend support to the Cohen and Klepper's (1996a, b) models, which suggest that large firms have a greater incentive to commit resources to process innovation than do small firms.

However, we found little evidence that capital investment is associated with process innovation. We tried a number of different specifications for capital investment, but none of these variables were significant in our models. This finding is difficult to interpret because of the problems of measuring capital intensity and the lack of time series data on capital investment. However, it would seem to contradict other research and suggests that greater efforts should be made to develop measures of capital intensity and to link it to process innovation.

In terms of the control variables, we found that investment in training is not significantly related to process innovation. We also found that the collaboration variable is significant throughout all the models and that the two associated parameter estimates are significantly different with a higher value for radical process innovation. This indicates that not only are collaborating firms better placed to become process innovators but that collaboration also increases the probability of being a radical rather than an incremental process innovator.

4.2 Complementarities analysis

Following the empirical approach of Arora and Gambardella (1990), Table 4 reports the correlations between the residuals from the multinomial logistic regression models explaining the three levels of process and product innovations. The results indicate that product and process innovations may be complementary. The finding also holds across different degrees of innovation. In both the process and the product innovation regressions, we find incremental and radical innovations to be highly correlated, conditioned on observables. All correlation estimates are significantly and positively correlated at the 1% level. This finding provides some support for Pisano's work and other studies, and it may point to the existence of complementarities between product and process innovations. It indicates that new products may beget new processes and vice versa. It also indicates that product and process innovations may not be unrelated in practice, and therefore, theories of innovation need to account for the mutual interaction between the two types of innovations. Attempts to draw strong inferences about the inducements for product and process innovations, such as have been developed in industrial economics models of Bertrand and Cournot competition, may produce unrealistic depictions

Table 4 Correlations between residuals from multinomial logistic regressions against process and product innovations

	Process innovation		Product innovation	
	Incremental	Radical	Incremental	Radical
Process innovation				
Incremental	1.0000			
Radical	0.3998	1.0000		
Product innovation				
Incremental	0.2441	0.1239	1.0000	
Radical	0.1478	0.2500	0.4484	1.0000

All correlations are significant at a 1% level.

Source: Own calculations on UK Community Innovation Survey data provided by the DTI.

of the contemporary features of corporate innovation (Bonanno and Haworth, 1998; Weiss, 2003).

5. Conclusions

Historical studies of technical change indicate that process innovation is responsible for a considerable proportion of productivity improvement and industrial change. Despite the importance ascribed to process innovation in these models and in historical studies of innovation, there are relatively few studies of the inducement of process innovation at the firm level. In order to redress this, this article used the UK innovation survey to examine the sources of process innovation, examining the relationship among product innovation, management strategy, and process innovation. We found that process innovation involves a number of heterogeneous activities. In order to examine what managers described as process innovations, we categorized the process innovations listed in the UK innovation survey and found that process innovation usually involves the introduction of new machinery and changes to the production process. It also involves the use of ICT and the adoption of new management practices, such as lean production. This descriptive analysis shows that process innovation often involves both organizational *and* technological changes in the processes of industrial firms.

At both the firm and industry levels, we found that process and product innovations are interdependent: radical product innovators are likely to be radical process innovators. In this respect, Pisano (1997) was right to suggest that new products generate new processes and vice versa. This finding could have implications for attempts to model the various inducements for product and process innovations. It suggests that previous models in industrial economics may have rather overemphasized the separation between process and product innovations. Indeed, our study suggests the two types of innovations should be seen as “brothers” rather than “distant cousins.”

We also found that product development strategies appear to play a role in shaping the ability of the firm to achieve radical process innovation. The significance of the cost-focus and product development strategy variables suggests that management choices about how best to organize the firm’s activities may shape the ability of the firm to achieve a process innovation. We found that the presence of R & D activities is associated with process innovation at the firm level and that the use of suppliers as an external knowledge source for innovation was also associated with process innovation. However, we found that customers and consultants had a negative effect on process innovation, indicating that process innovators may search more narrowly than product innovators. All of these results point to the importance of decision-making at the firm level in shaping the chances that a firm will be able to achieve a process innovation.

Future research on the sources of process innovation could productively link the sources of process innovation with industry-level characteristics. It is possible to argue that the nature of the competition and the technological regimes operating in an industry sector plays an important role in shaping the potential that firms will develop process innovations. This research could build on the diverse literature on how the nature of appropriability and technological opportunity differs across industries (Klevorick *et al.*, 1995; Malerba and Orsenigo, 1996). Such a study would complement our firm-level analysis and lead to a deeper understanding of the industry-level inducements for firm-level process innovation. However, as our study has shown, attention must be given to firm-level choices about innovative activities and how these choices shape the propensity for manufacturing firms to be process innovators. In addition, using new linked datasets of innovation surveys and production statistics, it may be possible to more directly explore the link between process innovation and productivity. Indeed, it could be extremely rewarding to explore the impact of process innovation on subsequent productivity improvements (Criscuolo *et al.*, 2003). The use of productivity and other external measures of performance would overcome some of the limitations of this study, which focused only on responses to the UK innovation survey. For example, such a study would also be able to directly test for the existence of complementarities.

Our study also has implications for the design and development of future innovation surveys. First, utilizing the unique features of the UK innovation survey, we were able to contrast the inducements for radical and incremental (or imitative) process innovations. In so doing, we found significant differences between the sources of different types of process innovations. This suggests that such a separation is useful and may yield a further and more refined understanding of process innovation. The distinction between process innovations that are new to the firm and those that are new to the industry is a particular feature of the UK innovation survey, a good example of where a country has adapted and changed the CIS to respond to its own particular interests. Second, the current generation of innovation surveys has come under increasing pressure to extend and refine the definition of process innovation as part of the shift in emphasis in innovation surveys away from technology-related product and process innovations (Smith, 2005). For example, the third edition of the Oslo Manual (2005) makes a distinction between process innovations and organizational innovations, separating the innovations that involve the development of new technology from changes in organizational arrangements. However, our analysis of process innovation has suggested that it remains difficult for managers to separate technological from the organizational innovations and that process innovations often involve both technological and organizational changes. The tension between the "technological" and the "organizational" changes remains unresolved in the study of process innovation and highlights the differing and incomplete understanding of the concept in the literature on the sources of innovation. Further refinements of the concept and a redefinition of process innovation could produce a new understanding. Such a redefinition of process innovation should account for the multidimensional character of process innovations, which often involve both technological and organizational changes.

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References

Abernathy, W. J. and P. L. Townsend (1975), 'Technology, productivity and process change,' *Technological Forecasting and Social Change*, **7**, 379–396.

Abernathy, W. and J. Utterback (1978), 'Patterns of industrial innovation,' *Technology Review*, **80**(7), 40–47.

Ahuja, G. (2000), 'Collaboration networks, structural holes and innovation: a longitudinal study,' *Administrative Science Quarterly*, **45**, 425–455.

Arora, A. (1996), 'Testing for complementarities in reduced-form regressions: a note,' *Economics Letters*, **50**, 51–55.

Arora, A. and A. Gambardella (1990), 'Complementarity and external linkages: the strategies of the large firms in biotechnology,' *Journal of Industrial Economics*, **38**(4), 361–379.

Athey, S. and S. Stern (1998), *An Empirical Framework for Testing Theories about Complementarity in Organizational Design*. National Bureau of Economic Research: Cambridge, MA.

Baldwin, J., P. Hanel and D. Sabourin (2002), 'Determinants of innovative activity in Canadian manufacturing firms,' in A. Kleinknecht and P. Mohnen (eds), *Innovation and Firm Performance*. Palgrave: London, pp. 86–111.

Bloodgood, J. M. and A. Bauerschmidt (2002), 'Competitive analysis: do managers accurately compare their firms to competitors?' *Journal of Management Issues*, **XIV**(4), 418–434.

Bonanno, G. and B. Haworth (1998), 'Intensity of competition and the choice between product and process innovation,' *International Journal of Industrial Organization*, **16**, 495–510.

Cabagnols, A. and C. Le Bas (2002), 'Differences in the determinants of product and process innovations: the French case,' in A. Kleinknecht and P. Mohnen (eds), *Innovation and Firm Performance*. Palgrave: London, pp. 112–149.

Cabral, R. and M. J. Leiblein (2001), 'Adoption of capital embodied process innovations in industries with learning by doing,' *Journal of Industrial Economics*, **49**(3), 269–280.

Cassiman, B. and Veugelers, R. (2002), 'Spillovers and R&D cooperation: some empirical evidence,' *American Economic Review*, **92**(4), 1169–1184.

Cohen, W. M. (1995), 'Empirical studies of innovative activities,' in P. Stoneman (ed.) *Handbook of the Economics of Innovation and Technological Change*. Basil Blackwell: Oxford, pp. 182–264.

Cohen, W. M. and S. Klepper (1996a), 'Firm size and the nature of innovation within industries: the case of process and product R&D,' *Review of Economics & Statistics*, **78**(2), 232–243.

Cohen, W. M. and S. Klepper (1996b), 'A reprise of size and R&D,' *Economic Journal*, **106**(437), 925–951.

Cohen, W. M. and D. A. Levinthal (1990), 'Absorptive capacity: a new perspective of learning and innovation,' *Administrative Science Quarterly*, **35**, 128–152.

Criscuolo, C., J. Haskel and R. Martin (2003), 'Building the evidence base for productivity policy using business data linking,' *Economic Trends*, **600**(November), 39–51.

Dahlin, K. and D. M. Behrens (2005), 'When is an invention really radical? Defining and measuring technological radicalness,' *Research Policy*, **34**, 717–737.

Damanpour, F. (1991), 'Organizational innovation: a meta-analysis of effects of determinants and moderators,' *Academy of Management Journal*, **34**(3), 555–590.

Damanpour, F. and S. Gopalakrishnan (2001), 'The dynamics of the adoption of product and process innovations in organizations,' *Journal of Management Studies*, **38**(1), 45–66.

Dosi, G. (1982), 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change,' *Research Policy*, **11**, 147–162.

DTI (2003), *UK Innovation Survey*. Department of Trade and Industry: London.

Edquist, C., L. Hommen and M. Mckelvey (2001), *Innovation and Employment: Process versus Product Innovation*. Edward Elgar: Cheltenham, UK/Lyme, US.

Evangelista, R. (1999), *Knowledge and Investment: The Sources of Innovation in Industry*. Edward Elgar: Cheltenham, UK.

Freeman, C. and C. Perez (1988), 'Structural crises of adjustment, business cycles and investment behaviour,' in G. Dosi *et al.* (eds) *Technical Change and Economic Theory*. Pinter Publishers: London, 38–66.

Freeman, C. and L. Soete (1997), *The Economics of Industrial Innovation*. Pinter Press: London.

Frenz, M., C. Girardone and G. Letto-Gilles (2005), 'Multinationality matters in innovation: the case of the UK financial services,' *Industry and Innovation*, **12**(1), 31–64.

Gatignon, H., M. L. Tushman, W. Smith and P. Anderson (2002), 'A structural approach for assessing innovation: construct development of innovation locus, type and characteristics,' *Management Science*, **48**(9), 1103–1122.

Hair, J. F. J., R. E. Anderson, R. L. Tatham and W. C. Black (1998), *Multivariate Data Analysis*. Prentice-Hall International, Inc.: Upper Saddle River, New Jersey.

Harcourt, G. C. and N. F. Laing (1971), *Capital and Growth*. Penguin: Harmondsworth, UK.

Hollander, S. G. (1965), *The Sources of Increased Efficiency: A Study of DuPont Rayon Plants*. MIT Press: Cambridge, MA.

Hosmer, D. W. and S. Lemeshow (2000), *Applied Logistic Regression*. John Wiley & Sons: New York.

Jaffe, A. B. and J. Palmer (1997), 'Environmental regulation and innovation: a panel data study,' *Review of Economics & Statistics*, **79**(4), 610–623.

Kaiser, U. (2002), 'Measuring knowledge spillovers in manufacturing and services: an empirical assessment of alternative approaches,' *Research Policy*, **31**(1), 129–149.

Klepper, S. (1997), 'Industry life cycles,' *Industrial and Corporate Change*, **6**(1), 145–182.

Klevorick, A. K., R. Levin, R. Nelson and S. Winter (1995), 'On the sources and significance of inter-industry differences in technological opportunities,' *Research Policy*, **24**, 185–205.

Kraft, K. (1990), 'Are product- and process-innovations independent of each other?' *Applied Economics*, **22**, 1029–1038.

Laursen, K. and A. J. Salter (2006), 'Open for innovation: the role of openness in explaining innovation performance among UK manufacturing firms,' *Strategic Management Journal*, **27**, 131–150.

MacPherson, A. D. (1997), 'A comparison of within-firm and external sources of product innovation,' *Growth and Change*, **28**(3), 289–308.

Mairesse, J. and P. Mohnen (2002), 'Accounting for innovation and measuring innovativeness: an illustrative framework and an application,' *American Economic Review*, **92**(2), 226–231.

Mairesse, J. and P. Mohnen (2005), 'The Importance of R&D for innovation: a reassessment using French survey data,' *Journal of Technology Transfer*, **30**(1/2), 183–197.

Malerba, F. and L. Orsenigo (1996), 'Schumpeterian patterns of innovation are technology specific,' *Research Policy*, **25**, 451–478.

Martinez-Ros, E. (2000), 'Explaining the decisions to carry out product and process innovations: the Spanish case,' *Journal of High Technology Management Research*, **10**(2), 223–242.

Michie, J., C. Oughton and M. Pianta (2002), 'Innovation and the economy,' *International Review of Applied Economics*, **16**(3), 253–264.

Milgrom, P. R. and J. Roberts (1995), 'Complementarities and fit: strategy, structure and organizational change in manufacturing,' *Journal of Accounting and Economics*, **19**, 179–208.

OECD (1997), *Proposed Guidelines for Collecting and Interpreting Technological Innovation Data: The 'Oslo Manual'*. Organisation for Economic Co-operation and Development: Paris.

OECD (2005), *Oslo Manual - Guidelines for Collecting and Interpreting Innovation Data*. Organisation for Economic Co-operation and Development: Paris.

Pavitt, K., M. Robson and J. Townsend (1987), 'The size distribution of innovating firms in the UK: 1945–1983,' *The Journal of Industrial Economics*, **35**(3), 297–316.

Pisano, G. (1997), *The Development Factory: Unlocking the Potential of Process Innovation*. Harvard Business School Press: Boston.

Porter, M. E. (1985), *Competitive Strategy*. Free Press: New York.

Porter, M. E. (1991), 'America's green strategy,' *Scientific American*, **April**, 168.

Powell, W. W., K. W. Koput and L. Smith-Doerr (1996), 'Interorganizational collaboration and the locus of innovation: networks of learning in biotechnology,' *Administrative Science Quarterly*, **41**(1), 116–145.

Rosenberg, N. (1982), *Inside the Black Box*. Cambridge University Press: Cambridge, MA.

Rouvinen, P. (2002), 'Characteristics of product and process innovators: some evidence from the Finnish innovation survey,' *Applied Economics Letters*, **9**(9), 575–580.

Salter, W. E. G. (1960), *Productivity and Technical Change*. Cambridge University Press: Cambridge, MA.

Simonoff, J. S. (2003), *Analyzing Categorical Data*. Springer: New York.

Smith, K. (2005), 'Measuring innovation,' in J. Fagerberg, D. C. Mowery and R. R. Nelson (eds), *The Oxford Handbook of Innovation*. Oxford University Press: Oxford/New York, pp. 148–177.

Stockdale, B. (2002), *UK Innovation Survey*. Department of Trade and Industry: London, pp. 1–11.

Stoneman, P. (2002), *The Economics of Technological Diffusion*. Blackwell: Oxford.

Tether, B. (2002), 'Who Co-operates for innovation, and why – an empirical analysis,' *Research Policy*, **31**(6), 947–967.

Tushman, M. L. and P. Anderson (1990), 'Technological discontinuities and dominant design: a cyclical model of technical change,' *Administrative Science Quarterly*, **35**, 604–633.

Tushman, M. L. and L. Rosenkopf (1992), 'Organizational determinants of technological change: toward a sociology of technological evolution,' *Research in Organizational Behavior*, **14**, 311–347.

Utterback, J. M. (1994), *Mastering the Dynamics of Innovation*. Harvard Business School Press: Boston, MA.

Utterback, J. M. and W. J. Abernathy (1975), 'A dynamic model of process and product design,' *Omega*, **3**(6), 639–656.

Vivero, R. L. (2002), 'The impact of process innovations on firm's productivity growth: the case of Spain,' *Applied Economics*, **34**, 1007–1016.

Von Hippel, E. (1988), *The Sources of Innovation*. Oxford University Press: New York and Oxford.

Weiss, P. (2003), 'Adoption of product and process innovations in differentiated markets: the impact of competition,' *Review of Industrial Organization*, **23**, 301–314.

Womack, J. P., D. T. Jones and D. Roos (1990), *The Machine that Changed the World*. Rawson Associates: New York.

Zahra, S. A. and G. George (2002), 'Absorptive capacity: a review, reconceptualisation, and extension,' *Academy of Management Review*, **27**(2), 185–203.

Zucker, L. G., M. R. Darby and M. B. Brewer (1998), 'Intellectual human capital and the birth of U.S. biotechnology enterprises,' *American Economic Review*, **88**(1), 290–306.