Are different forms of innovation complements or substitutes?

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Are Differing Forms of Innovation Complements or Substitutes?

Abstract
Purpose – The purpose of this article is to provide an empirical analysis of whether differing forms of innovation act as complements or substitutes in Irish firms' production functions.
Design-Methodology/Approach – The approach adopted by this paper is empirical in nature. Data is obtained for approximately 582 firms from the Irish Community Innovation Survey 2004-06. Four forms of innovation activity are identified; new to firm product, new to market product, process and organisational innovation. Formal tests for complementarity and substitutability are applied to these types of innovation to assess whether they have a complementary effect on firms' turnover.
Findings – The results suggest that there is a substantial degree of complementarity among different forms of innovation. Out of six possible innovation combinations, three are complementary while none exhibit signs of substitutability.
Social Implications – From a business perspective, the importance of organisational change to facilitate technological innovation is highlighted while from a policy perspective the importance of the incentivisation of organisation and process innovation is also highlighted.
Originality/Value – To date most research has focused on the impact of various forms of innovation, in isolation, on firms' productivity. They do not consider whether these forms of innovation may in fact be linked, and that by implementing two or more innovations simultaneously, the combined benefits may be greater than the sum of the parts.
Keywords: Innovation, Productivity, Complementarity, Substitutability
Paper Type: Research Paper

1. Introduction

This paper analyses whether different forms of innovation act as complements or substitutes in firms' production functions. This is accomplished through the estimation of a knowledge augmented production function (Griliches 1979; 1995) and subsequent testing for supermodularity (complementarity) and submodularity (substitutability) in this production function (Mohnen and Roller 2005). This enables the paper to establish the nature of the relationship between different forms of innovation and their impact on firm level productivity (Cassiman and Veugelers 2006; Percival and Cozzarin 2008). The data utilised is derived from the Irish Community Innovation Survey (CIS) 2004-06.

The importance of innovation for firm performance is highlighted by endogenous growth models such as those developed by Romer (1986) and Lucas (1988). These models suggest that firms can exploit new products, process and organisation in order to improve firm performance through a number of mechanisms (Mansury and Love 2008; Roper, Du et al. 2008). Numerous empirical studies have documented the impact of firm level innovations on firm performance. For example, Roper et al. (2006) highlights the importance of innovation, proxied for by research and development (R&D) performance, on firms' export performance while Crépon et al. (1998) and Johansson and Lööf (2009) demonstrate the importance of new product innovation on firm turnover per worker and value added. Other papers which also analyse the impact of innovation on firm performance are Klomp and Van Leeuwen (2001: 2006), Janz et al. (2003), Roper et al. (2008) and Hall et al. (2009). However, the extent to which innovations complement/substitute one another in the production function is relatively under-documented.

The majority of research on complementarity and substitutability in innovation systems focuses on innovation strategies, as oppose to innovation outputs. For example, Love and Roper (2009) focus on complementarity in how firms source knowledge for innovation while Cassiman and Veugelers (2006) analyse the nature of the relationship between internal R&D and external R&D. These papers have provided important insights into how firms innovate but do not address the questions of whether there may be economies of scope in innovation output itself.

This paper attempts to overcome this deficiency in the innovation management literature by providing an empirical analysis of the degree of complementarity and substitutability in the innovation processes of Irish firms. This paper makes two contributions to the innovation management literature. Firstly, it builds on studies such as Love and Roper (2009) and Schmiedeberg (2008), which assess whether complementarities exist among different forms of innovation inputs, by analysing innovation outputs using the supermodularity framework. That is to say this paper analyses complementarity between types of innovations as oppose to complementarities among R&D or barriers to innovation. In doing so it provides an insight into possible synergies which may exist among innovation activities, allowing firms to target the implementation of the types of innovation which when combined lead to the greatest productive gains. Secondly, using the Community Innovation Survey, this paper identifies four distinct forms of innovation, distinguishing between technological and non-technological innovation as well as different levels of "newness" of innovation. This is accomplished by including organisational innovation in the complementarity analysis which allows for potential synergies to be identified between technological and non-technological innovation types and also by identifying two types of product innovation which can be distinguished between based on their level of radicalism.

This paper provides tests of strict complementarity across the innovation activities identified. In doing so this paper provides important insights into the innovation process of firms and the extent to which firms can exploit complementarities in innovation activities. While papers such as Ar and Baki (2010) and Crépon et al. (1998) analyse the impact of innovation on firm performance, this paper expands upon their work by assessing the degree to which complementarity/substitutability exists among different forms of innovation in firms' production functions.

In order to complete this analysis, this paper identifies and distinguishes between four types of innovation; new to market and new to firm product innovations, process innovations and organisational innovations. The distinction between these four forms of innovation is crucial as each type of innovation may have differing effects on firms' productivity and may complement/substitute other forms of innovation (OECD 2005). It is expected that the nature of the pair-wise complementarity between these four forms of innovation may vary (Athey and Stern 1998; Roper, Youtie et al. 2010). One such example which can be envisaged is a situation whereby a firm which introduced a new product may require a change in its production process to facilitate the production of this new good (Kraft 1990; Swann 2009); thereby, implying a complementary relationship.

The remainder of the paper is structured as follows. The next section provides a discussion of the key theory underpinning the nature of innovation and productivity and potential complements or substitutes present in this. This is followed by an outline of the Irish CIS dataset. The empirical methodology employed by this paper is then discussed. Following this the results are presented and analysed. The final section concludes.

2. Review of Literature

2.1 Classifying Innovation

As the central focus of this paper is to analyse the degrees of complementarity/substitutabiltiy between different forms of innovation, it is important to clearly define each type of innvoation considered. This section will classify the types of innovation considered by this paper. Initially, differing forms of product innovation are discussed and a distinction is made between radical and incremental innovation. This is followed by a description of the distinction between product and process innovation. Organisational innovation is then outlined.

The OECD (1991) define innovation as "an iterative process initiated by the perception of a new market and/or new service opportunity for a technological-based invention which leads to the development, production and marketing tasks striving for the commercial success of the invention" (Garcia and Calantone 2002; 112). Garcia and Calantone (2002) note that this definition implies that the innvoation process is iterative, with different levels of innovativeness. For instance, the first introduction of a new innovation differs from the reintroduction of an improved innovation. They argue that product innvoation can be categorised into three types; (i) radical innovation, (ii) really new innovation and (iii) incremental innovation.

This distinction is somewhat captured by the OECD (2005), who classify product innovations as either new to market or new to firm. The relevance of the OECD definitions for this paper is that the Irish CIS is designed based on the OECD's (2005) Oslo manual and therefore the measures used in the empirical analysis take the form of new to firm and new to market innovation. Following Garcia and Calantone (2002), in this paper new to market innovation could be deemed a *really new* innovation as it is the first introduction of a product into a firm's market (however, it cannot be classified as a radical innovation as it may have existed on other markets previously). New to market innovation is defined as a new or significantly improved good or service which was released onto the market before a firm's competitors, however, it may have already been available in other markets (OECD 2005). While new to firm innovation can be deemed an *incremental/imitative innovation*, as this form of innovation is the introduction of a new product to the market by the firm, however, the product is already being sold onto the market by competitors (OECD 2005).

Schumpeter (1934) makes another important distinction between product and process innovation. Process innovation is concerned with the identification of new and more effective internal operations and is often associated with the ability to produce greater quantities of output or operate at a lower cost (Martinez-Ros and Labeaga 2009). The OECD (2005) define process innovation as the implementation of a new or significantly improved production process, distribution method, or support activity for your goods or services.

In addition to process innovation, the OECD (2005) distinguishes between process innovation and organisational innovation. Organisational innovation is defined as the introduction of (i) significantly changed organizational structures, (ii) advanced management techniques or (iii) new or substantially changed corporate strategic orientations (OECD 2005). Firms which engage in any one of these three forms of organizational innovation can be classified as an organizational innovator. Organisational innovation is often classified as non-technological innovation. Mol and Birkinshaw (2009) identify that this form of innovation is often incremental in nature and is distinctly differentiated from product and process innovation.

As this paper utilizes the Irish Community Innovation Survey (CIS), which is based upon the OECD's (2005) classification of innovation activities, the above definitions of innovation are utilised throughout this paper. Four distinct forms of innovation are analysed; (i) new to market product innovation, (ii) new to firm product innovation, (iii) process innovation and (iv) organisational innovation.

2.2 Innovation and Firm Performance

Having defined innovation it is important to note the consensus in the literature regarding the importance of innovation for firm performance. Griliches (1979; 1995) identifies that firm performance can be augmented by their technological progress. This is consistent with endogenous growth models developed by Romer (1986) and Lucas (1988) which suggest that investment in research and development can result in increasing returns to scale; allowing firms to continually improve their productive effort. Hansen and Birkinshaw (2007) and Roper et al. (2008) describe the process whereby firms source knowledge for innovation, transform this knowledge into innovation output and exploit this innovation output for productivity gains as the innovation value chain. Central to the innovation value chain are the varying effects of differing forms of innovation on productivity (OECD 2005; Griffith, Huergo et al. 2006; Hall, Lotti et al. 2009).

Kline and Rosenberg (1986) note that there is recognition needed that there are many "black boxes" through which a firm's performance can be influenced by innovation; suggesting that each of these various types of innovation, product, process and organizational innovation may have differing effects on firms' performance. Product innovation may increase turnover, process innovation may reduce costs and organizational innovation can impact the structure of the firm and its production process (OECD 2005; Swann 2009).

Indeed, studies based on the methodology developed by Crépon, Duguest and Mairesse (1998), hereafter referred to as the CDM methodology after the authors who first instigated it, emphasises the importance of innovation output for firm performance. Crépon et al. (1998) find that firms which innovate have higher levels of turnover per employee. This is consistent with Griffith et al. (2006) and Johansson and Lööf (2009) who indicate that both product and process innovation have a positive impact of firms turnover per worker. Johansson and Lööf (2009) and Roper et al. (2008) further suggest that these forms of innovation also increase firms' value added per employee. Klomp and Van Leeuwen (2001) find that firms which introduce new product or process innovations have higher levels of sales per employee and also exhibit higher levels of employment growth. These studies highlight the important role innovation activities play in explaining productivity differentials across firms.

2.3 The Meaning of Complementarity

Before developing hypotheses regarding potential complementarity between innovation types it is important to define the meaning of the term complementarity. Milgrom and Roberts (1990) note that the term complementarity can have diverse meanings in economics. In line with Milgrom and Roberts (1990) this paper defines complementarity to mean the relationship among groups of activities. The key characteristic of this definition is that " if the levels of any subset of the activities are increased, then the marginal return to increases in any or all of the remaining activities rises" (Milgrom and Roberts 1990: 514). Hou and Mohnen (2011) further note that when discussing the complementarity of economic activities two criterion must be met. Firstly, they note that adopting one activity must not preclude the firm from adopting the other, if it does then the two items cannot be complements as they cannot be undertaken together. Secondly, identically to Milgrom and Roberts (1990), they note that when it is possible to implement each activity separately, the sum of the benefits of the activities introduced separately is not greater than the benefit of doing both together.

Schmiedeberg (2008) utilises this concept of complementarity for her analysis of different R&D activities for German manufacturing plants. Defining complementarity across R&D activities as existing if the engagement of a firm in two types of R&D activity simultaneously resulted in greater returns to the firm than engagement in either of these forms of R&D separately. Therefore, when applying the concept of complementarity to the study of the complementarity of innovation activates in subsequent sections of this paper, complementarity relates to whether firms which undertake two forms of innovation simultaneously gain more benefit than firms which undertake the same forms of innovation separately. Essentially testing whether the benefit derived from the simultaneous combination of two innovation activates is greater than the sum of its parts.

2.4 Are Different forms of Innovation Complements?

As identified above, while papers such as Crépon et al. (1998), Klomp and Van Leeuwen (2001; 2006), Lööf and Heshmati (2002; 2006) and Roper et al. (2008) analyse the importance of product and process innovation for firm performance, they do not address whether these forms of innovation complement or substitute one another in the augmented production function. Freeman and Soete (1997) note that since Schumpeter there has been general acknowledgement of the existence of complementarity among product and process innovation. They note that radical product innovations may in turn lead to changes in processes of production. This is supported by Swann (2009) and Mohnen and Roller (2005), who suggest that the introduction of one type of innovation may necessitate the introduction of a different form of innovation.

Kraft (1990) proposes a hypothesis that both product and process innovation are not independent of each other, and that through the performance of one the likelihood of undertaking the second increases. He notes that frequently the manufacture of a new product will only be possible if a new production process is introduced. A reverse causality is also posited, however, Kraft (1990) suggests that it is less likely. He notes that a change to the production process may result in the firm possessing the capabilities to introduce new products. Indeed, when his hypotheses are tested, Kraft (1990) notes that firms which engage in product innovation are more likely to introduce process innovations, but firms which engage in process innovation are not more likely to engage in product innovation.

However, Martinez-Ros and Labeaga (2009), who propose a similar hypothesis, conclude that firms which engage in process innovation are in fact more likely to engage in product innovation and *vice versa*. This is consistent with Schumpeter's (1975) view, that a positive relationship exists between product and process innovation. This complementarity relationship is further supported by papers such as Martinez-Ros (2000), Miravete and Pernías (2006) and Percival and Cozzarin (2008). As this paper identifies two types of product innovation, new to firm and new to market innovation, it facilitates a more comprehensive analysis of the relationship between product and process innovation. This distinction is important, as noted by Reichstein and Salter (2006) the strength of the complementary relationship between product and process innovation can depend on the degree of novelty of the innovation. It is expected that new to market innovation would be a more novel form of innovation than new to firm innovation (OECD 2005). Based on these theories the following hypotheses are proposed by this paper:

> H1: New to firm product innovation and process innovation complement one another in firms' production functions.

> H2: New to market product innovation and process innovation complement one another in firms' production functions.

Following this, it is possible to posit a relationship between different forms of product innovation. As discussed in Section 2.1, new to firm innovations can be viewed as distinctly different to new to market innovations. While Love and Mansury (2007) note significant differences in the drivers of both new to firm and new to market innovation Doran and O'Leary (2011) also note a significant overlap in terms of the number of firms engaging in both new to firm and new to market innovations. Reichstein and Salter (2006) investigate the nature of the relationship between different forms of the same type of innovation. Their paper focuses on the extent of complementarity between radical and non-radical product and process innovation. While this analysis is not possible in this paper, a distinction can still be made between new to market (*really new*) and new to firm (*incremental/imitative*) innovation. This makes it possible to assess whether a complementary relationship exists between different degrees of product innovation.

Martinez-Ros and Labeaga (2009) find a strong persistence in product innovation; suggesting that firms are more likely to introduce new product innovations if they have previously product innovated. This may suggest that firms which have engaged in new to market innovation may be more likely to subsequently engage in new to firm innovation and *vice versa*. Following from this hypothesis three is proposed:

> H3: New to market product innovation and new to firm product innovation complement one another in firms' production functions.

One of the key contributions of this paper is to consider, not just technological innovation, such as product and process innovation, but also non-technological innovation, in the form of organizational innovation. As suggested by Schumpeter (1934), the successful introduction of an innovation into a firm often necessitates changes in organizational and management structures to facilitate it. This raises the possibility that, as oppose to complementarities simply existing among product and process innovation, the adoption of organizational innovations may also exert a complementary effect. Schmidt and Rammer (2007) propose that non-technological innovation can augment technological innovation, thereby improving firm performance. They conclude that firms which combine organizational innovation with product and process innovation achieve higher profit margins. Mol and Birkinshaw (2009) provide further support for this hypothesis by concluding that firms which undertake product or process innovation are more likely to engage in organizational innovation. This suggests the following hypothesis to be tested:

> H4: Organisational innovation complements product and process innovation in firms' production functions.

Percival and Cozzarin (2008) note that due to the different nature of innovation activates it can be expected that each individual type of innovation will exhibit different pair-wise complementary or substitutability relationships. This is supported by Zinger (2002) who suggests that different patterns of complementarities may exist among different forms of innovation. Hypotheses (1) through (4) detail the expectations, based on theory, of the nature of the relationship between each of the types of innovation considered by this paper.

However, when considering the nature of the relationship between different forms of innovation Athey and Stern (1998), who develop a theoretical model which predicts that in the short run product and process innovations act to complement one another, note that internal firm heterogeneity can impact on this relationship. Roper et al. (2010) further suggests that complementary relationships exist between different forms of innovation activity; however, they note that the extent to which this is observed varies. They find that UK firms are better able to exploit complementarity between innovation types than Georgian and Catalonian firms. The authors again point to the heterogeneity which exists between firm characteristics; in their case driven by differences between firms among countries. These studies highlight the importance of controlling for heterogeneity among firms when considering complementarity/substitutability. This variation in the ability of firms across countries to derive complementarities in the innovation process raises the question as to whether Irish firms are apt at exploiting economies of scope across innovation activities. This paper provides a contribution to the literature by analysing complementarity in innovation performance across Irish firms while also controlling for firm heterogeneity. Forms of heterogeneity controlled for include firm size, capital intensity and sectoral differences.

3. The Irish Community Innovation Survey 2004-06

The data set utilised by this paper is the Irish Community Innovation Survey (CIS) 2004-06. The rationale for choosing the Irish CIS as the basis of this analysis is that it provides a large scale representative survey of the innovation activities of Irish firms. The survey is stratified to represent the diverse firm sizes and sectoral composition observed across the Irish economy. The use of the CIS survey to address issues of complementarity is consistent with Schmiedeberg (2008). This survey was conducted jointly by Forfás (Ireland's national policy advisory body) and the Central Statistics Office in Ireland. The survey is directed to companies employing more than 10 persons engaged in a range of sectors. The CSO and Forfás jointly conducted a postal survey in October 2007. Consistent with the OECD's Oslo manual, the survey includes a reference period, which in this case is 2004 to 2006, for innovation inputs and outputs (OECD 2005). Prior to the CIS 2004-06, all CIS surveys were conducted singly by Forfás. The CIS questionnaire is available from the Central Statistics Office of Ireland's website. A total of 4,150 surveys were issued with 1,974 responses. However, when controlling for capital per employee in production function, and a number of other variables, the number of available firms decreases to 582. The main cause for this is the lack of a measure of capital in the CIS. Therefore, a proxy must be utilised to control for the effect of capital intensity on firm performance; the construct of this proxy is discussed further below. The proxy variable is not available for all firms in the sample, therefore, reducing the sample size.

The target for the Irish CIS are the complete range of manufacturing sectors, with selected service sectors (Forfás 2008). The motivation for the CIS survey is to provide a comprehensive survey of the innovation performance of Irish firms. The survey is conducted as part of the European wide Community Innovation Survey project and is completed every two years (Forfás 2008).

This paper uses data on four forms of innovation obtained from the Irish CIS; organizational, process, new to firm and new to market innovation. The definitions used are taken directly from the Irish CIS survey and conform to the definitions outlined in Section 2.1. Firstly, organizational innovation is defined in the Irish CIS as the implementation of new business practices for organising procedures, new methods of organising work responsibilities and decision-making or new methods of organising external relations with other firms or public institutions. However, these occurrences must be the result of strategic decisions taken by management and exclude mergers or acquisitions, even if for the first time. Process innovation is defined as the implementation of a new or significantly improved production process, distribution method, or support activity for firms' goods or services.

Product innovation is broadly defined as the market introduction of a new or significantly improved good or service with respect to its capabilities, user friendliness, components or sub-systems. However, this is further refined to indicate whether the firm introduced a product innovation which was new to the firm or new to the market. New to market innovation is defined as the introduction of a new or significantly improved good or service onto the market before competitors, while new to firm innovation is defined as the introduction of a new or significantly improved good or service that was already available from competitors in the market. This distinction between new to firm and new to market innovation is in line with Percival and Cozzarin (2008) distinction between world first innovation and new to firm innovation.

The Irish CIS asks firms to indicate whether they have engaged in any of these forms of innovation throughout the reference period 2004-06. This results in a series of binary variables which indicate whether the firm engaged in these differing innovation activities. This allows for the binary variable to take the form of zero and one, where zero indicates that the firm did not engage in the innovation activity considered and one indicated that the firm did engage in the innovation activity considered. The percentage of firms which engaged in each form of innovation is displayed in Table 1. For the innovation variables, the percentages of firms which performed the different forms of innovation activity are presented. A series of mutually exclusive binary variables is generated to indicate the sector in which a firm operates. It can be observed that 44% of firms engaged in organizational innovation, 31% engaged in process innovation, 25% in new to firm innovation and 22% in new to market innovation.

In addition to these four forms of innovation, the size of the firm and the capital per worker are also controlled for. It has been shown in the literature that these factors are vital to control for in firms' knowledge augmented production functions (Crépon, Duguest et al. 1998; Roper, Du et al. 2008). One problem faced in controlling for the capital intensity of firms is that the Irish CIS contains no data on the capital stock possessed by businesses. However, Doran and O'Leary (2011) identify that a suitable replacement can be found through the use of firms' capital acquisitions throughout the reference period on advanced machinery, equipment and computer hardware or software to produce new or significantly improved products or processes. They note that the inclusion of this variable proxies adequately for the capital stock of the firm. While, ideally, the capital stock per worker should be included this is not possible for a lot of studies which use CIS type datasets as this information is not available. Mansury and Love (2008) also use a flow variable, using capital investment per employee, as a proxy for capital stock for their sample of US manufacturing firms while Doran and O'Leary (2011) use an identical measure of capital to this paper. The average number of employees is 124 with a standard deviation of 525 while the average capital per employee is €6,952 with a standard deviation of €49,064.

Another source of substantial heterogeneity across firms' performance is the sector in which the firm operates (Pavitt 1984). In order to control for potential sectoral effects five sectoral dummies are included. The sectors surveyed in the CIS are the complete range of manufacturing sectors and three services sectors: *Wholesale, Transport, Storage and Communication; Financial Intermediation;* and *Computer, Architecture and Engineering Services.* This paper also divides manufacturing into *High-Tech Manufacturing* and *All Other Manufacturing*, giving a total of five different sectoral classifications. These sectoral classifications are consistent with Doran and O'Leary (2011). It can be observed that 25% of firms are in *High Technology Manufacturing*, 36% are in *All Other Manufacturing*, 20% are in *Wholesale, Transport, Storage and Communication*, 6% are in *Financial Intermediation* and 13% in *Computer, Architecture & Engineering Services*.

The measure of productivity used in the analysis is the turnover per worker for firms. Klomp and Van Leeuwen (2006), in an analysis of the effects of innovation on firm level productivity, measure productivity using both turnover and value added and conclude that turnover provides more satisfactory estimations than value added. Similarly, Johansson and Lööf (2009) also demonstrate that turnover per worker can be used as an adequate measure of the performance of firms in a knowledge augmented production function framework.

Table 1: Descriptive Statistics of the Irish CIS 2004-06

	Mean	s.d.
Turnover per Employee (€)	€548,044	€2,171,000
Innovation		
Organizational (%)	44%	n.a.
Process (%)	31%	n.a.
New to Firm (%)	25%	n.a.
New to Market (%)	22%	n.a.
Sector		
High Technology Manufacturing (%)	25%	n.a.
All Other Manufacturing (%)	36%	n.a.
Wholesale, Transport, Storage & Communication (%)	20%	n.a.
Financial Intermediation (%)	6%	n.a.
Computer, Architecture & Engineering Services (%)	13%	n.a.
Control Variables		
Capital per employee (K)	€6,952	€49,064
Labour (L)	124	525

Source: Community Innovation Survey 2004-06

4. Empirical Methodology

This paper employs a methodology similar to that of Mohnen and Röller (2005), Love and Roper (2009) and Sharapova and Kattuman (2010). The methodology allows for an analysis of whether various combinations of innovation output act as complements or substitutes in firms' production functions. The types of innovation output considered are; new to firm product innovation, new to market product innovation, process innovation and organisational innovation. To test for complementarity a test of supermodularity is applied which is consistent with that outlined by Athey and Stern (1998).

Alternative test specifications are possible when considering tests for complementarity. For example, Kraft (1990) utilises a simultaneous equation framework to consider the implications for firms engaging on both product and process innovation. While Roper et al. (2010) utilises a series of probit models to assess whether there is a correlation between firms which engage in different forms of innovation. The use of interaction terms can also be used to assess complementarity. However, the advantages of using strict tests for supermodularity and submodularity is that it is possible to control for all combinations of innovation activity whilst avoiding potential endogeneity problems experienced in other specifications. The disadvantage is that a large sample size is required, restricting the degree to which sub-categories of firms can be isolated and analysed.

4.1 A Simple Two-Output Example

Suppose there are two potential innovation outcomes; product and process innovation. These are represented as binary indicators of whether a firm introduced (i) neither type of innovation, (ii) process innovation only, (iii) product innovation only or (iv) both product and process innovation. These outcomes can be expressed as the set C where $C = \{00, 01, 10, 11\}$ and each outcome refers to the innovation type performed by the firm. For example, a firm may opt to introduce no new innovation (in this case C=00) or the firm may choose to introduce both product and process innovation (in this case C=11).

Extending the above example, supermodularity in the production function is present when the inequality constraint (1) is satisfied.

$$I(10) + I(01) \leq I(00) + I(11) \qquad (1)$$

Where (10) represents product innovation, (01) process innovation, (00) no innovation and (11) both product and process innovation. The left hand side, therefore, represents the effects should product and process innovation be implemented separately. The right hand side displays the effects should both product and process innovation be implemented simultaneously. The inequality constraint (1) can be rewritten as (2) for the purpose of testing.

$$I(10) + I(01) - I(00) - I(11) \leq 0 \qquad (2)$$

The intuition from this example is that introducing product innovation is more efficient when process innovation is already in place and *vice versa*; which occurs when the right hand side of equation (1) is greater than the left hand side, or when the inequality equation (2) holds. This may be due to the existence of economies of scope in the adoption of such strategies; essentially that the combination of the two forms of innovation is greater than the sum of its parts (Miravete and Pernías 2006).

4.2 Modelling Four Innovation Outputs

When expanding this model to include four types of innovation this methodology becomes more complex. In order to analyse the effects of various combinations of innovation output on firm performance a series of mutually exclusive binary variables for each combination must be generated (Cassiman and Veugelers 2006; Love and Roper 2009; Strube and Resende 2009). Table 2 details these binary variables and the corresponding implemented innovations. It can be noted that in total 16 possible states exist for firms.

Table 2: Binary Innovation Indicators Classifications

Associated Coefficient	Variable Description
γ_0	No Innovation Introduced
γ_1	Organizational Innovation
γ_2	Process Innovation
γ_3	Organizational & Process Innovation
γ_4	Firm Innovation
γ_5	Firm & Organizational Innovation
γ_6	Firm & Process Innovation
γ_7	Firm & Organizational & Process Innovation
γ_8	Market Innovation
γ_9	Market & Organizational Innovation
γ_{10}	Market & Process Innovation
γ_{11}	Market & Process & Organizational Innovation
γ_{12}	Market & Firm Innovation
γ_{13}	Market & Firm & Organizational Innovation
γ_{14}	Market & Firm & Process Innovation
γ_{15}	Market & Firm & Process & Organizational Innovation

Given that sixteen innovation state variables are included in the model there is the potential that multicollinearity could bias the results of the estimation. In order to assess the degree to which multicollinearity may be present a correlation matrix of the innovation state variables is generated. This table is presented as Appendix 1 and shows that the degree of correlation between the variables is sufficiently low to imply that multicollinearity among the regressors will not be a problem in the estimation of equation (3) below.

It is hypothesised that all four innovation types are pair-wise complementary (Leiponen 2005; Mohnen and Roller 2005; Percival and Cozzarin 2008). However, there is the possibility for substitutability to also be observed. To test the inequality constraints implied by supermodularity an estimation of the firm's production function is required. This can be specified as:

$$P_i = \sum_{l=0}^{15} \gamma_i s_i + \beta Z_i + \varepsilon_i \qquad (3)$$

Where P_i is a measure of a firms performance, s_i represents the set of 16 innovation state variables (displayed in Table 2), γ_i is the associated coefficient of the state variable, Z_i is a vector of firm specific control variables, β is the vector of control coefficients and ε_i is the error term. Where Z_i is defined as:

$$Z_i = (Capital_i Size_i, Sector_i)$$

Where $Capital_i$ is an indicator of the capital per employee in the firm, $Size_i$ is an indicator of the size of the firm and $Sector_i$ is a series of binary variables indicating the sector a firm operates in. The importance of controlling for firm level heterogeneity when testing for supermodularity is emphasized by Athey and Stern (1998) and Mohnen and Röller (2005). Specifically, Cohen and Klepper (1996) note that firm innovation activity may depend on the firm size and the resources which can be devoted to research and development. This is also found to be the case in other empirical estimations of knowledge augmented production functions (Crépon, Duguest et al. 1998; Janz, Lööf et al. 2003; Lööf and Heshmati 2006).

As per Mohnen and Röller (2005) and Percival and Cozzarin (2008) the null hypothesis for complementarity has the supposition of a negative value while the alternative hypothesis is that the inequality is positive or equal to zero. For example, the analysis of new to firm innovation and new to market innovation is expanded to the following (where the coefficients are defined as in Table 2).

H_0:	H_1:
$-\gamma_0+\gamma_4+\gamma_8-\gamma_{12}<0$	$-\gamma_0+\gamma_4+\gamma_8-\gamma_{12}\geq 0$
and	*or*
$-\gamma_1+\gamma_5+\gamma_9-\gamma_{13}<0$	$-\gamma_1+\gamma_5+\gamma_9-\gamma_{13}\geq 0$
and	*or*
$-\gamma_2+\gamma_6+\gamma_{10}-\gamma_{14}<0$	$-\gamma_2+\gamma_6+\gamma_{10}-\gamma_{14}\geq 0$
and	*or*
$-\gamma_3+\gamma_7+\gamma_{11}-\gamma_{15}<0$	$-\gamma_3+\gamma_7+\gamma_{11}-\gamma_{15}\geq 0$

In the case of four types of innovation output, new to firm and new to market innovation can only be deemed strict complements if undertaking both types of innovation together generates a greater return than performing them separately, regardless of whether the firm engages (i) in no other innovation activity, (ii) in process innovation as well, (iii) in organisational innovation as well or (iv) in both process and organisation innovation as well. The first inequality shows the outcome for firms which just perform new to market and new to firm innovation ($-\gamma_0+\gamma_4+\gamma_8-\gamma_{12}<0$). The second equation shows the outcome when the firm engages in new to firm innovation and new to market innovation while also undertaking organisational innovation ($-\gamma_1+\gamma_5+\gamma_9-\gamma_{13}<0$). The third equation shows the outcome when the firm engages in new to firm innovation and new to market innovation while also undertaking process innovation ($-\gamma_2+\gamma_6+\gamma_{10}-\gamma_{14}<0$). Finally the fourth equation shows the outcome when the firm engages in new to firm innovation and new to market innovation while also undertaking both organisational and process innovation ($-\gamma_3+\gamma_7+\gamma_{11}-\gamma_{15}<0$). All four equations must show that new to firm and new to market innovation undertaken together returns greater benefits than undertaking them separately, regardless of whether other forms of innovation are also undertaken at the same time. If any equation shows that the two forms of innovation are not complementary then the hypothesis of strict complementary among those innovation types is rejected. Therefore, for the hypotheses outlined in Section 2 to be tests it is necessary to jointly test all for inequality constraints.

Similarly, the remaining restrictions for the other pairings can be expressed by writing the pair wise restrictions for complementarity for every potential combination of innovation outputs.

The test accepts H_0 (strict complementarity of the two objects) whenever the constraints are jointly negative. However, rejection of the null hypothesis does not imply that the two objects are substitutes. The alternative hypothesis includes "or", which implies that some of the subset may have mixed signs. In this case neither complementarity nor substitutability is present. A strict test for submodularity can be defined as:

H_0:	H_1:
$-\gamma_0 + \gamma_4 + \gamma_8 - \gamma_{12} > 0$	$-\gamma_0 + \gamma_4 + \gamma_8 - \gamma_{12} \leq 0$
and	*or*
$-\gamma_1 + \gamma_5 + \gamma_9 - \gamma_{13} > 0$	$-\gamma_1 + \gamma_5 + \gamma_9 - \gamma_{13} \leq 0$
and	*or*
$-\gamma_2 + \gamma_6 + \gamma_{10} - \gamma_{14} > 0$	$-\gamma_2 + \gamma_6 + \gamma_{10} - \gamma_{14} \leq 0$
and	*or*
$-\gamma_3 + \gamma_7 + \gamma_{11} - \gamma_{15} > 0$	$-\gamma_3 + \gamma_7 + \gamma_{11} - \gamma_{15} \leq 0$

As in the earlier case, the null hypothesis specifies that for submodulatiry to exist all of the constraints must be jointly greater than zero while to reject the null hypothesis only one or more of the constraints must be less than zero.

To test these hypotheses, a Wald test is applied. For each pair of innovation types, four inequalities must be simultaneously tested. This application is consistent with Mohnen and Röller (2005) and Love and Roper (2009). Critical values for the Wald test are derived from Kodde and Palm (1986).

5. Empirical Results

The OLS estimation of equation (3), firms' knowledge augmented production function, is displayed in Table 3. The sixteen unique innovation state variables are included, as well as the controls for labour, capital and sectoral heterogeneity. Before discussing whether innovation activities within the production function complement or substitute one another, it is interesting to observe the effect of firm specific factors on productivity.

Table 3: OLS Estimation of Production Function

Variable	Coefficient	Stad. Error
Innovation Indicator		
No Innovation Introduced	11.14191***	(0.3337)
Organizational Innovation	10.39222***	(0.3024)
Process Innovation	10.64741***	(0.2510)
Organizational & Process Innovation	10.70597***	(0.2255)
Firm Innovation	11.04934***	(0.2969)
Firm & Organizational Innovation	10.72056***	(0.3612)
Firm & Process Innovation	10.34751***	(0.3566)
Firm & Organizational & Process Innovation	10.66095***	(0.2548)
Market Innovation	10.96117***	(0.3616)
Market & Organizational Innovation	10.22968***	(0.3767)
Market & Process Innovation	10.69642***	(0.4261)
Market & Process & Organizational Innovation	10.90593***	(0.2586)
Market & Firm Innovation	10.77744***	(0.3346)
Market & Firm & Organizational Innovation	10.83784***	(0.3329)
Market & Firm & Process Innovation	11.0147***	(0.3452)
Market & Firm & Process & Organizational Innovation	10.73856***	(0.2361)
Company Specific Factors		
Labour[2]	0.255399***	(0.0383)
Capital[2]	0.272478***	(0.0296)
Sector[4]		
All Other Manufacturing	-0.0758	(0.1275)
Wholesale, Transport, Storage & Communication	0.53989***	(0.1487)
Financial Intermediation	0.2325	(0.2127)
Computer, Architecture & Engineering Services	-0.3257*	(0.1744)
Obs.		582
Degrees of Freedom		560
R^2		0.2505

Note 1: Dependent variable is the log of turnover per employee.
2: Variables are expressed in natural logarithms
3: *** indicates significance at the 1% level, ** indicates significance at the 5% level and * indicates significance at the 10% level
4: High-technology manufacturing is the sectoral reference category.

The significant labour coefficient suggests that larger firms are found to exhibit higher levels of turnover per worker. This is consistent with existing literature on innovation augmented production functions and suggests increasing returns to scale in production (Roper, Du et al. 2008). It can also be observed that firms with a higher degree of capital per worker are more productive. Again, this is also consistent with the existing literature on the knowledge augmented production function (Crépon, Duguest et al. 1998; Janz, Lööf et al. 2003; Love and Mansury 2007). A sectoral effect can also be observed with firms in the *Wholesale, Transport, Storage and Communication* sector being more productive than firms in the *High Technology manufacturing* sector and firms in the *Computer, Architecture and Engineering Services* sector being less productive than firms in the *High Technology manufacturing* sector. The significance of these variables highlights the importance of controlling for heterogeneity across firms.

Turning to the main focus of this paper, to test for possible complementarity and substitutability in firms' innovation activity, a series of joint Wald tests must be estimated in accordance with the hypotheses establisher earlier (Mohnen and Roller 2005). The results of these Wald tests are displayed in Table 4. Each combination of innovation activities displayed in Table 4 relates to the hypotheses developed in Section 2. The combination of organisational and process innovation (1 – 2), organisational and new to firm innovation (1 – 3) and organisational and new to market innovation (1 – 4) is given as hypothesis 4. The combination of process and new to firm innovation (2 – 3) and process and new to market innovation (2-4) represents hypothesis 1 and 2 respectively. Finally, the combination of new to market and new to firm innovation (3 – 4) represents hypothesis 3.

Table 4: Wald Test Statistics for Supermodularity and Submodularity in Innovation Activity

Combinations of Innovation Activity	1 - 2	1 - 3	1 - 4	2 - 3	2 - 4	3 - 4
Supermodularity Test	0.1156	0.2311	0.4622	0.9245	0.1000	0.0578
Submodularity Test	2.0030	0.7511	5897.27	225.10	0.9823	0.3467

Note 1: Innovation activity definitions; 1 organizational innovation, 2 process innovation, 3 new to firm innovation and 4 new to market innovation.

2: Critical values at the 10% significance level are 1.642 for lower bound and 7.094 for upper bound. Based on Kodde and Palm (1986).

Care is required when interpreting the results of the Wald tests of supermodularity (complementarity) and submodularity (substitutability). It is not possible to utilise the traditional f-distribution to calculate a critical value for these tests (Athey and Stern 1998; Mohnen and Roller 2005) and, therefore, critical values are obtained from Kodde and Palm (1986).

The test statistics are assessed using the lower bound value of 1.642 and the upper bound value of 7.094. If the Wald statistic presented in Table 4 is below the lower bound then the null hypothesis of supermodularity or submodularity can not be rejected while if the test statistic lies above the upper bound then the null hypothesis is rejected. Values which lie between the upper and lower bound are inconclusive. While the statistics may initially indicate a complementarity relationship, strict supermodularity is only observed when the null hypothesis of supermodularity is not rejected and the null hypothesis of submodularity is rejected. For strict submodularity the reverse must hold. Therefore, both tests must be considered in conjunction with one another to establish whether complementarity/substitutability exists. This means that for strict complementarity to be observed the supermodularity test static must lie below 1.642 while the corresponding submodularity test statistic must lie above 7.094. For weak complementarity the supermodularity test statistic must again lie below 1.642 while the corresponding submodularity test statistic must lie above 1.642. The reverse applies for strict and weak substitutability (Love and Roper 2009).

It can be observed that initially, each innovation activity appears to act as a complement to each other form of innovation as all the Wald statistics are below the lower bound value of 1.642. However, when turning to the submodularity tests it can be observed that in half of the cases it is also not possible to reject the null hypothesis of submodularity, as the values are again below the critical value of 1.642. This suggests that the nature of the relationship between half of the forms of innovation is neither strictly supermodular nor submodular. This ambiguous result is not uncommon in relation to testing for the presence of supermodularity and submodularity (Leiponen 2005; Love and Roper 2009; Strube and Resende 2009). The tests require that all four restrictions, outlined in the methodology section, hold. However, when considering innovation it is possible for the nature of the relationship between two forms of innovation to be altered should an additional, third form of innovation be undertaken. Therefore, it is not possible to refer to these forms of innovation as strict complements or substitutes as the nature of the relationship varies.

However, in the instances of organisational and process innovation, organisational and new to market innovation and process and new to firm innovation the null hypothesis of supermodularity is not rejected while the null hypothesis of submodularity is not accepted. In these instances, it is possible to conclude that there is evidence that these forms of innovation complement one another. Thus providing support for hypothesis 1 and partial support for hypothesis 4. For hypothesis 4 it is found that organisational innovation complements process innovation and new to market innovation, however, no evidence is found to support the final element of hypothesis 4, that new to firm innovation and organisational innovation are complements. These results are summarized in Table 5.

Table 5: Summary of Patterns of Complementarity and Substitutability in Innovation Activity

	Organizational Innovation	Process Innovation	New to Firm Innovation
Process Innovation	C		
New to Firm Innovation	-	C*	
New to Market Innovation	C*	-	-

Note 1: C indicates complementarity.
2: * indicates failure to reject null hypothesis is also accompanied by rejection of the alternative hypothesis.

It can be observed that out of a possible six relationships three exhibit complementary behaviour. This implies that firms which introduce these types of innovation together gain more of a benefit than firms which introduce these forms of innovation separately.

These results provide support for Hypotheses 1 and 4 while they fail to provide any support for Hypotheses 2 and 3.

Hypothesis 1 suggests that a complementary relationship exists between new to firm innovation and process innovation. This supports Kraft's (1990) views that the manufacture of a new product may be facilitated by new production processes or that a change to the production process may result in the firm possessing the capabilities to introduce new products. The finding of a complementary relationship between process innovation and product innovation (specifically new to firm product innovation in the case of this paper) is consistent with Martinez-Ros (2000), Miravete and Pernías (2006) and Percival and Cozzarin (2008).

Hypothesis 4 suggests that firms which engage in organisational innovation as well as different forms of technological innovation (product and process innovation) may experience complementary synergies. This finding supports Schumpeter's (1934) assertion that the successful introduction of an innovation into a firm often necessitates changes in organizational and management structures to facilitate it. The evidence presented here suggests that non-technological innovation can augment technological innovation, thereby improving firm performance. Without these organizational changes the new production process may not achieve its full potential. Similarly, the complementary relationship between new to firm innovation and organisational innovation may be due to the need for businesses to adopt new organisational practices to fully exploit new to market innovations. These findings are consistent with Schmidt and Rammer (2007) and Mol and Birkinshaw (2009) who also suggest a close relationship exists between organizational and technological innovation.

Hypotheses 2 and 3 suggest a complementary relationship between new to market innovation and process innovation and new to market product innovation and new to firm product innovation. The lack of significant complementarity effects among these types of innovation suggest a lack of synergies between these varieties. Therefore, while each form of innovation appears to act as a complement to at least one other form of innovation, the effects are not unilateral. The specific combination of innovation outputs matter to achieve complementary benefits. For example, the results suggest that for a firm to maximize its benefit from the introduction of a new to market innovation, it is the co-introduction of organization innovation, as oppose to process or new to firm innovation, which is key.

6. Conclusion and Implications

This paper analyses whether innovation activities act as complements or substitutes in firms production functions. Four different forms of innovation are considered; organisational, process, new to firm and new to market innovation. The data set utilised is the Irish Community Innovation Survey (CIS) 2004-06. A knowledge augmented production function is estimated and the innovation activities considered are tested for supermodularity and submodularity.

The results indicate that out of the six possible pair-wise relationships analysed, three exhibit complementarity relationships while none exhibit substitutability. Each form of innovation is found to complement at least one other form of innovation. However, complementary relationships are not all pervasive. Firms which undertake (i) organisational and process innovation, (ii) organisational and new to market innovation or (iii) process and new to firm innovation experience complementarity benefits. Essentially, the combination of the two types of innovation together resulted in a greater gain to firms' productive performance than if the two forms of innovation had been introduced individually. These findings suggest that certain subsets of innovation activities exhibit economies of scope (Miravete and Pernías 2006).

One of the key implications of the results is that non-technical innovation, in the form of organisational innovation, appears to exhibit a strong complementary relationship with technological innovation. The nature of this relationship may flow in two possible directions. Firstly, it may suggest that the implementation of new process innovations and new to market innovations benefit greatly when organisational structures evolve around these innovations. This is similar to Schumpeter's (1934) argument that for organisations to fully reap the benefits of their innovations they must adopt their working practices. A second plausible explanation is that the re-organisation of the organisational structure can promote and enhance firms' ability to develop and bring to fruition new to market and process innovations. This echoes Kline and Rosenberg's (1986) and Hansen and Birkinshaw's (2007) argument that firms must develop their organisation structure to be conducive to the introduction of new innovations.

The implications of this result for businesses are that an openness to organisational change and a willingness to adopt at the organisational level are central to the successful adaptation of technological innovations (Drucker 1998). Firms which fail to introduce organisational change face the prospects of not obtaining the full benefits of their innovation and may also face the prospect of not being in a position to develop new to market and process innovations.

The second main implication of this paper is that no innovation is an island. Each type of innovation acts to complement at least one other form of innovation. This suggests that businesses with an overly narrow focus on specific forms of innovation may be unintentionally limiting the potential benefits from their innovations. The implications are that firms should pursue a multi-faceted approach to innovation. This may involve ensuring that new processes are introduced alongside new products or that the organisation is open to change.

From the perspective of policy makers the findings of this paper have mixed implications. As the focus of Irish innovation policy rests on technological innovation, being strongly focused on product innovation, the finding of complementary relationships between new to market and organisational innovation and new to firm and process innovation suggests that the oversight of Irish innovation policy, in overlooking these others forms of innovation may be short-sighted. By not encouraging the simultaneous development of process and organisational innovation within businesses, policy makers may inadvertently be negating potential benefits arising to firms from economies of scope. This suggests that a more balanced approach to the promotion of innovation activities should be adopted by policy makers. This could be in the form of providing additional supports to firms whose sole focus is process innovation or in incentivising new forms of organisational structure. This would enable firms to exploit synergies in the implementation of innovations which exhibit economies of scope while also providing support for innovations which appear to be independent of these scope economies. This finding may also be extrapolated to other countries' innovation policies.

When considering the generalisation of these results across other geographical contexts care must be taken. As noted by Love and Roper (2009) and Roper et al. (2010) the relationship between innovative activities can vary. This is further highlighted by Schmiedeberg (2008) who also notes that the relationship between can vary depending on the context analysed. Roper et al. (2010) note that when comparing two European regions with the United States that innovation activities display different relationships across each of the three regions they study. They note that country heterogeneity can impact on the interdependence of innovation activities. Therefore, case specific research may be necessary should the characteristics of firms vary substantially for that contained in the Irish CIS.

Linked with this, when deriving conclusions it is important to remember that the data set utilised is cross-sectional in nature. This means that complementarity/substitutability of innovation activities across time cannot be considered. It is possible that the nature of the relationship between innovation activities may evolve over time. Therefore, while it is not possible here, the analysis of this issue through a panel data framework would be welcomed as it would allow the treatment of these issues across time. Further to this, the use of larger dataset may facilitate the splicing of data by sub-categories such as by sector or firm size. This would also allow for an analyses of whether the nature of the relationship across innovation types varies depending on the size/sector of the firm. While this paper has control for potential heterogeneity caused by firm size and sector, due to the size of the sample, it is not possible to provide a more detailed analyse of the potential sectoral/size effects on complementarity/substitutability in firms' innovation activities.

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Appendix 1: Table A1

	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_{12}	γ_{13}	γ_{14}	γ_{15}
γ_0	1.000															
γ_1	-0.037	1.000														
γ_2	-0.055	-0.064	1.000													
γ_3	-0.088	-0.102	-0.151	1.000												
γ_4	-0.036	-0.042	-0.062	-0.100	1.000											
γ_5	-0.029	-0.034	-0.050	-0.080	-0.033	1.000										
γ_6	-0.030	-0.035	-0.052	-0.083	-0.034	-0.027	1.000									
γ_7	-0.059	-0.068	-0.101	-0.162	-0.067	-0.054	-0.055	1.000								
γ_8	-0.029	-0.034	-0.050	-0.080	-0.033	-0.027	-0.027	-0.054	1.000							
γ_9	-0.026	-0.030	-0.045	-0.071	-0.029	-0.024	-0.024	-0.048	-0.024	1.000						
γ_{10}	-0.022	-0.026	-0.038	-0.062	-0.025	-0.020	-0.021	-0.041	-0.020	-0.018	1.000					
γ_{11}	-0.055	-0.064	-0.094	-0.151	-0.062	-0.050	-0.052	-0.101	-0.050	-0.045	-0.038	1.000				
γ_{12}	-0.034	-0.039	-0.058	-0.093	-0.038	-0.031	-0.032	-0.062	-0.031	-0.027	-0.024	-0.058	1.000			
γ_{13}	-0.033	-0.038	-0.056	-0.090	-0.037	-0.030	-0.031	-0.061	-0.030	-0.027	-0.023	-0.056	-0.035	1.000		
γ_{14}	-0.032	-0.037	-0.055	-0.088	-0.036	-0.029	-0.030	-0.059	-0.029	-0.026	-0.022	-0.055	-0.034	-0.033	1.000	
γ_{15}	-0.093	-0.107	-0.159	-0.254	-0.105	-0.084	-0.087	-0.171	-0.084	-0.075	-0.065	-0.159	-0.098	-0.095	-0.093	1.000

Note 1: Definitions of coefficients are given in Table 2 above.