The Role of Public Policy and High-performance Work Practices in Supporting Business Innovation

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Contents

Abbreviations

List of abbreviations

Abbreviation	**Description**
HRM	Human resource management
SHRM	Strategic human resource management
HEH	human-capital enhancing HRM
MEH	Motivation enabling HRM
OEH	Opportunity enabling HRM
R&D	Research and development
HPWS	High performance work system
AMO	Ability, Motivation, Opportunity

List of tables and figures

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Above all, I am most grateful to the almighty God for life, for introducing this phase into my life and the grace to experience it fully.

Declaration

I declare that the content of this thesis “The Role of Public Policy and High-performance Work Practices in Supporting Business Innovation” is my own work and no part of this thesis has been previously submitted to any other university for any degree. The content in Chapter 2 and Chapter 3 was previously submitted and presented at the DRUID 2021 conference in Copenhagen. The content in Chapter 4 was previously submitted and presented at the ISBE 2022 conference in York. The extent to which other authors work has been used is referenced in the text and bibliography. Any errors or omissions in this thesis is the sole responsibility of the author. This thesis contains 50249 words without bibliography and Table of Content, and thus adheres to the requirement of Warwick Business School, University of Warwick.

Abstract

Innovation is broadly defined as ‘doing new things’ and has been widely acknowledged as one of the key contributors to sustainable economic growth and national competitiveness. Achieving innovation, particularly among the business sector depends on various factors including innovation policy and Human Resource Management (HRM). Innovation policy is a form of government intervention including measures, programs, grants, and incentives intended to support the creation and diffusion of innovation. Governments use innovation policy to create stimulating systems and favourable environment in which innovation activities are realised.

In an increasingly competitive market, the success and growth of businesses are affected by the ability to extract productive employees’ role behaviours to impact performance. The role of HRM is to use systems of HR practices which enhance employees’ competencies, enable favourable employees’ behaviours, and create opportunities for employees’ participation. The subject of this research project is the effects of HRM practices and innovation policy support, particularly the innovation policy mix, on firms’ performance in terms of R&D investment and innovation outputs. “Policy mix” is a concept which concerns the composition of policies in combinations and how they might interact to mutually shape each other’s effectiveness.

In view of the above, this research first examined the R&D input and innovation output additionalities of public innovation policy mix to contribute to the limited literature on the link between policy mix and innovation, and to extend previous studies relating to policy effect on firm innovation outcomes. Estimation of the impact of policy instruments in isolation may be biased due to hidden effects when other instruments that firms receive are not considered. There is therefore a call on researchers to rather examine the interaction effect of policy instruments in a mix to avoid under – or over - estimation of individual policy effect. Drawing upon information on public R&D supports from the UK innovation survey (UKIS) and coarsened exact matching with propensity score matching techniques, this research demonstrates that a mix of R&D tax incentives and R&D grants leads to both input and output additionalities in treated firms in comparison to untreated firms – confirming the complementary effect perspective, which suggests that public support can induce beneficiary firms to invest more efforts into innovative activities and/or experience higher innovation performance than would otherwise in the absence of the support. The results are consistent along dimension of firms’ size, productivity, industry, and technology and knowledge intensity.

Secondly, based on the Ability-Motivation-Opportunity (AMO) framework and a novel data match between the UKIS and the UK Employer Skills Survey, this thesis delineated three HRM systems to extend the literature on our understanding of the relationship between HRM and performance, and thus contributes to the limited literature on the causal impact of HRM systems on firm innovation. The findings evidence different components of HRM systems have unique and heterogeneous impact contingent on the kind of innovation, and the type of firm along dimensions of size and industry.

Chapter 1

1 Introduction

“Creativity is thinking up new things. Innovation is doing new things.” —Theodore Levitt

1.1 Background to research projects

By its capacity to increase the rate of productivity growth in the economy, innovation has been widely acknowledged as one of the main driving forces of sustainable economic growth and national competitiveness. Although public sector and household sector innovations contribute to growth trajectories of any economy, highly industrialised economies depend largely on the private sector innovation for ensuring a continuous advancement in technological development for the attainment of economic growth.

Schumpeter, the father of the study of innovation, defined innovation as ‘new combinations’ of elements that already exist (Schumpeter, 1942). Also, for the past twenty-five years, the Oslo Manual (OECD/Eurostat, 2005) has provided definitions of innovation for use in statistical measurement in the business sector. These innovation definitions pertain to product, process and two types of organizational innovation (i.e., marketing and organization). The current definitions of innovation used for the statistical measurement of innovation in the business sector are articulated in paragraphs 146 and 150 of the Oslo Manual (OECD/Eurostat, 2005). Paragraph 146 stipulates an innovation to be the implementation of ‘a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations’. A common feature of an innovation is that it must have been *implemented*. A new or improved product is implemented when it is introduced on the market. New processes, marketing methods or organizational methods are implemented when they are brought into actual use in the firm’s operations (paragraph 150). While product and process innovation are required to be ‘new or significantly improved’, marketing and organization innovation are required to be ‘new’. In this thesis, three innovation measures are considered, namely, product, process and organization (which comprises of innovation in marketing and/or organization methods).

Inspired by the original work of Schumpeter (1911, 1942), academics and practitioners around the globe have examined and provided tremendous insight into the nature, sources and determinants of innovation (Love and Roper, 1999; Salter and Alexy, 2014). Broadly, the landscapes of innovation are characterised by well-established categories, such as the development of new products, processes, services, marketing method or organization methods. Over the years, scholars have also sought to characterise innovation by degree and type. One classic distinction is between radical and incremental, which suggests the degree of novelty introduced by an innovation into the economic system. Another classic distinction is between product innovation, which involves the creation and launching of identifiable goods and services, and process innovation, which often involves changes in operations, tasks, and ways of working in an organization.

Over the years, researchers of innovation have offered a greater understating of how innovation happens (Martins, 2012). Many researchers have focused on the classical investment in R&D, either done in-house or bought-in R&D. Another stream of research has focused on firms' openness to external sources of innovation such as suppliers, clients or customers, competitors, consultants, commercial laboratory/R&D enterprises, universities or other higher education institutions, government research organizations, or private research institutes (Roper et al., 2017), which allows firms to draw in ideas to deepen the pool of technological opportunities available to them (Chesbrough, 2003). Research indicates that searching widely and deeply across a variety of external search channels can provide ideas and resources that help firms gain and exploit innovative opportunities, although there may be moments whereby over-search in terms of breadth and depth may hinder innovation performance (Roper et al., 2013; Love et al., 2014; Roper et al., 2017). Another stream of research has focused on investigating how businesses can use human resource practices to influence individual's behaviour, skill, knowledge and abilities for innovation performance. Some researchers have also focused on public innovation supports and their effectiveness for innovation performance (Roper et al., 2004).

This current research focuses on the latter two streams of research since, first, research on how human resource practices influence innovation is very limited, and second, governments invest significant amounts of funding in support of R&D and innovation within the economy and policy makers need to ascertain the effectiveness of public support instruments.

Before proceeding further, it should be noted that the unit of analysis of this research is the firm. The entire thesis is based on firm-level information pooled from three cross-sectional UK Innovation Surveys (UKIS) and three cross-sectional UK Employer Skills Surveys (ESS). The UKIS collects data from businesses about various aspects of their innovation-related activities and contributes to the European-wide Community Innovation Survey (CIS). The ESS on the other hand provides information on labour market indicators including skills, training, and high-performance work practices.

R&D and innovation policy instruments are the mechanisms by which policy makers and funding agencies allocate funding to private firms to achieve R&D and innovation policy objectives. In the UK, there are various forms of public R&D and innovation policy tools available to firms. These include direct R&D grants, indirect R&D tax incentives, or a mix of both (policy mix).

The concept of "policy mix" is based on the general understanding that the way in which one policy instrument influences the innovation behaviour of firms is connected to the ways in which other instruments influence the same target firms. The policy mix concept acknowledges that policy instruments may interact with the portfolio of already existing instruments for a given target group or technology. At the core of the policy mix concept are the interactions among the policy instruments which imply that the impact of individual policy instrument is influenced by the coexistence of other instruments (Rogge and Reichardt, 2016). The interdependencies of influence emanating from the direct and indirect operations and outcomes of policy instruments essentially impact the overall effect of the policy mix and thus the attainment of policy objectives (Flanagan et al., 2011), and the over-all effect could be complementary, trade-offs or neutral depending on the degree of consistency among the effects of the individual policy tools. This concept is applied to the research questions in Chapter 2 and Chapter 3 of the research project, respectively the R&D input additionality of policy mix and innovation output additionality of the policy mix.

1.2 Policy mix: Evaluating the input additionality of public R&D Supports

The first research paper focuses on the effectiveness of public Research and Development support (R&D) in stimulating additional R&D efforts in the private sector. Public support for private R&D is generally considered as necessary in optimizing the level of firms' private R&D investment. The fundamental argument in the public policy literature is whether public supports substitute businesses' private investment efforts, complement them, or even favour their increase (Cunningham et al., 2013). Moreover, firms often benefit from mixes of public support instruments which tend to interact and influence the effect of one another. The central argument in the literature has been the need to analyse the joint effect of support instruments in mixes to avoid under- or over-estimation of individual instrument effects (Rogge and Reichardt, 2016). This part of the research is motivated by the fact that while the individual impact of public supports (e.g., R&D tax incentives and R&D grants) has been extensively considered in the literature, the analysis of the impact of a mix of the two policy tools, particularly as it applies to the UK economy is still limited. The first research paper therefore, focuses on analysing whether public R&D support, individually or in a mix, complements or substitutes private R&D efforts. The conceptual analysis is built around the mechanisms of how public support stimulates additional private R&D investment by influencing the market and economic factors that drive firms' R&D decisions.

Using coarsened exact matching with propensity score matching techniques (Iacus et al., 2012) and data sourced from three consecutive UK Innovation Surveys, the study finds evidence (based on final matched treated samples of 1,377 tax-incentives-only recipients, 371 grant-only recipients and 486 both tax-incentives and grant recipients) which suggests that, the probability of investing in R&D is 27 percentage points higher among firms that received policy mix than firms that received no public funding (i.e. the control group). The policy effect is 31.4 percentage points among firms that received tax incentives only and 13.2 percentage points among grant-only recipients when compared with firms that received no public support.

This suggests a strong complementarity between public support and private R&D investment, and rejects the substitution hypothesis in the literature. The policy mix effect is however smaller than the tax-incentives-only effect and larger than the grant-only effect, suggesting a strong complementarity effect of tax incentives on grant supports, or grant supports weakening the effect of tax incentives.

1.3 Estimating policy mix effects: Grants and tax credit complementarities for innovation outcomes

It is often argued that public support may stimulate more private R&D investment but this does not necessarily lead to additionality in innovation outputs (Czarnitzki and Hussinger, 2018). Meanwhile, while most policy evaluation studies focus on the impact of public intervention on

R&D investment, studies on the relationship between public intervention and firms' innovation outputs is quite limited, particularly regarding the effectiveness of the UK's innovation policy in spurring firm innovation. On the other hand, since firms often receive a combination of different policy, for the policy maker, there is the question of whether policy mix can achieve synergies and positive complementarities, and how any negative interaction between instruments can be abased (Cunningham et al., 2013). The second research project therefore focuses on evaluating the effectiveness of the UK's R&D tax incentives and R&D grants in facilitating firm innovation. The innovation impact of the individual policy tools as well as a mix of both policy schemes are considered. The innovation output considered are product innovation and process innovation. The conceptual argument for the research is built around the mechanisms through which public policies impact firm innovation output by influencing the efficiency and scale of firms' knowledge -search and -acquisition activities and secondly, by influencing the efficiency with which firms transform knowledge assets into innovation.

Based on a propensity score matching technique and 42,323 observations sourced from the UKIS, the study finds evidence which suggests that R&D grants in isolation do not promote firm innovation while R&D tax incentives in isolation promote both product innovation and process innovation in participating firms. The impact is 10.5 percentage points and 5.6 percentage points respectively for product innovation and process innovation when compared with firms that received no public support. The policy mix impacts are higher as expected: 16.1 percentage points for product innovation and 11.2 percentage points for process innovation – thus, suggesting a strong complementarity between grant and tax incentives.

1.4 Causal effects of strategic human resource management systems on firm innovation

The third paper examines how Human Resource Management (HRM) impacts firm innovation performance through the strategic application of HR practices. To survive intensifying market competition, firms have turned to effective utilization of their human capital (Kaufman, 2015) to attain high-level performance. Organization-level human capital resources which are created from the collective interactions of individual skills, knowledge, abilities and other characteristics (Ployhart and Moliterno, 2011) represent an essential input for organizations' strategic business plan development and execution (Huselid, 1995). While a substantial number of studies have examined the impact of HRM practices on firm performance outcomes such as productivity, employee turnover and employee commitment, the analysis of how HRM practices impact firm innovation has received little attention in the literature.

Theoretically, the link between HRM and organizational performance has either been studied from the behavioural perspective, whereby HRM impacts performance by influencing and aligning employees' attitudes and behaviours, or through the human capital and resource-based view, whereby HRM contributes to employees' knowledge, skills and abilities (Jiang, Lepak et al., 2012; Seeck and Diehl, 2017), or the Ability-Motivation-Opportunity (AMO) framework which argues that HRM impact performance by contributing to human capital, motivating employees to dispense productive role behaviour and by providing opportunity for employees participation. The research conceptual framework is based on the latter where it is argued that HRM practices impact firm innovation by enhancing human capital, motivating individuals to deploy their competencies, and providing the opportunity for individuals to use their skills and motivation to impact performance. Meanwhile, current studies examining the relationship between HRM practices and firm performance have done so either by the individual best-practice approach or the system approach (Boxall and Purcell, 2003; Delery and Doty, 1996). The assumption underlying the individual best-practice approach is that organizations will improve their performance if they implement certain best HR practices (Wood, 1999). The system approach, on the other hand, emphasises the need to integrate the operation of bundles of individual HR practices in a complementary manner (Wood, 1999; Boxall and Macky, 2009; Boxall and Purcell, 2022).

In the current study, the system approach is adopted to directly link three HRM systems, namely, the Human-capital Enhancing HR (HEH) system, the Motivation Enabling HR (MEH) system, and the Opportunity Enabling HR (OEH) system to three different innovation outcomes (product, process and organization innovation). The HEH system consists of HR practices that relate to the staffing of the organization and employee development through training. HR practices in this system includes on- or off- the job training and the use of quality employee identification processes. The MEH system includes practices such as personal pay and bonuses, flexible benefits, post-training assessment and performance review. The final system, OEH, consists of HR practices that entails the design and organization of work in the firm. These include, putting employees into teams to work on projects, task variety, task discretion and flexible working.

Analysis is based on merged data from the UKIS and ESS datasets. The average marginal effects estimation obtained from logit regressions indicate that, all things being equal, the application of the OEH increases the likelihood of product innovation and organization innovation respectively by 6% and 9%. Similarly, ceteris paribus, the application of the HEH system increases the probability of process innovation and organization innovation by 9% and 13% respectively. The MEH system seems to impact product innovation with an average marginal effect of 11percentage. That is, while both motivation-enabling and opportunity-enabling systems promote product innovation, organization innovation is promoted by human-capital enhancing and opportunity-enabling systems. Process innovation on the other hand is promoted only by a human-capital enhancing system.

1.5 Integrated firm heterogeneity findings

It is reasonable to suspect that firms' responsiveness to public funding, HRM systems and, the resultant effect in innovation performance may vary considerably across different firm characteristics. Major results in the innovation and policy studies indicate that firm heterogeneity matters in the way in which firms respond to support and/or organize innovation activities. Differentials in firm-specific characteristics and contexts present specific set of opportunities and challenges that greatly influence the way in which firms organize their innovation activities and also the way in which they react to public support. Specifically, the R&D and innovation performance of firms varies greatly by industry, size, productivity level, technological and knowledge intensity (Roper et al., 2017). Similarly, firms' responsiveness to public support varies across firm size, industry, productivity, R&D and knowledge intensity (Castellacci and Lie, 2015; Vanino et al., 2019). Similarly, firms' innovation responsiveness to HRM strategies may vary across firm size and industries. In view of this, each of the three research topics outlined above provided further analysis in respect of differentials in innovation benefit across multiple firm-specific characteristics including size, industries, degree of technology and knowledge intensity. Specifically, results from the R&D input additionality study indicate that the additionality effect of tax incentives is larger in small firms, the service industry, and low-tech sectors (Castellacci and Lie, 2015). Similarly, the policy mix effect on R&D investment is stronger for firms in the service, low-tech and low-knowledge-intensive sectors. Results from the strategic HRM research also indicate that for manufacturing firms, HRM only impacts organization innovation, which is attainable by adopting either a Human-capital enhancing system or an opportunity-enabling system. Innovation in the service industry is promoted by two HRM systems, namely motivation-enabling and opportunity-enabling systems. Meanwhile innovation in small firms is promoted by Human-capital enhancing and opportunity enabling systems. Finally, the overall results from the innovation output additionality research indicate that output additionality of tax incentives is higher for medium-large firms, manufacturing firms, high-tech firms and knowledge intensive firms. The innovation benefit of policy mix on the other hand is higher for medium-large firms, service, low-tech and knowledge intensive sectors.

1.6 Contribution of thesis

This thesis makes several contributions to the literature on firm-level innovation, public policy supports and strategic HRM:

1. The thesis contributes to the limited literature on the additionality effects of innovation policy mix. Empirical understanding of policy mix effects has received little attention in the literature (Guerzoni and Raiteri, 2015), particularly with regards to the UK public support. This thesis addresses this limitation by providing insight into the effectiveness of UK's public innovation policy mix (i.e., R&D tax incentives and R&D grants) in facilitating firms' innovation input (internal R&D) and outputs (product and process innovation). Additionally, the study documents the effectiveness of the individual policies in facilitating additionalities in R&D investment and innovations. This thesis therefore extends previous studies by providing insight into the innovation input and output effects on one side, and tax incentives, grants and policy mix on the other side. It also provides insight into the complementary relationship of the public policy tools and firms' own private innovation efforts and performance.

2. The study contributes to the limited literature on the output additionality effect of public innovation support. In comparison with input additionality, the output additionality of public innovation supports has received little attention in the literature. This thesis investigates the output additionality effects of three different innovation policies (e.g., tax incentives only, grants only, and a mix of tax incentives and grants) and contributes to the limited literature on the second-order effects of public innovation policies by providing an output additionality effects of tax incentives and extending our understanding of how the adoption of tax incentives in isolation may influence firms'

innovation outcome – thereby contributing to the limited literature on the output additionality of tax incentives which has been noted in the literature (e.g., Cerulli and Poti, 2012; Castellacci and Lie, 2015). Secondly, the study offers insight into the innovation output effect of R&D grants in isolation, and contributes to the limited literature on the effectiveness of direct R&D supports in facilitating firms' innovation output. Thirdly, the study provides insight into how firms' innovation output may be influenced by combining both direct and indirect innovation supports – a rarely considered aspect in the public innovation support literature (Guerzoni and Raiteri, 2015; Rogge and Reichardt, 2016). Finally, this thesis considers two different innovation outcomes (product and process innovation) across the three policy interventions, and thus provides insight and extends the literature on how specific public interventions may influence different innovation outcomes.

3. Another novel part of this research is that most policy evaluation studies consider the additionality effect for the whole observation sample, and seldom investigate differences in the additionality across firm heterogeneities (Castellacci and Lie, 2015). This study not only looks at the whole sample but provides insight into the differing effect of tax-incentives-only, grants-only and a mix of both across multiple firm characteristics such as size, industry, degree of technology and knowledge intensity, and across productivity frontiers.

4. The study introduces a novel data that allows contribution to the causal understanding of how three different HRM systems may influence three different firm-level innovation outcomes (i.e., product, process and organization innovation), thereby, extending our understanding on strategic HRM systems as levers for developing firms' competitive advantages through innovation and, contributing to the limited literature on strategic HRM and its link to innovation. Secondly, the study provides insight into the differential effects of the HRM systems across industries and firm size.

1.7 HRM and public policy as drivers of innovation

This thesis is underpinned by two different but related research themes: the relationship between public supports and strategic HRM practices on one side and firm-level innovativeness on the other. Both HRM practices and innovation policies determine the success of innovation and drive differentials in firm-level innovativeness. Although firms have total control of the internal aspect which is the HRM, policy intervention is external to the firm, meaning that in terms of HRM practices firms need to organise themselves for innovation. Nonetheless, both are crucial for building firms' internal capabilities that are associated with innovation (Weber and Rohracher, 2012; Lenihan et al., 2019; Gahan et al., 2021). Public support impact firms' internal R&D engagement, and both R&D and HRM practices are internal mechanisms for capacity building. Figure 1.1 depicts how the HRM and policy themes relate to firms' capacity for innovation.

Generally, the fundamental reason why any firm will implement an HRM practice is to enhance its capacity for higher performance. Similar argument can be made in regard to why a firms may decide to participate in public funding. The general argument in the literature is that HRM practices have the capacity to generate innovative capabilities in firms by influencing their employees' ability, knowledge and behaviour in the desired strategic direction (Zhou et al., 2013). On the other hand, firm learn, acquire and enhance their knowledge through funded project. Public interventions enable firms develop core research skills to develop transferable and integrative skills (McKelvey and Ljungberg, 2017) and skills capabilities for external partnerships (Ahn et al., 2020). HRM practices also serve as microfoundations for the development of firms' intellectual capability in terms of their workforce networks, human capital, social capital, and organizational capital (Glaister et al., 2018). It has been shown that HRM practices and public policies promote capacity to absorb, organise and generate relevant knowledge for innovation. They promote the development of unique knowledge resources (Lopez-Cabrales et al., 2009) which facilitate capacity for further learning, and external knowledge and technology transformation (Wang and Zhou, 2022). They also have the capacity to build firms' internal adaptive and resilience capabilities for innovation in turbulence business environment, particularly in SMEs (Wei and Lau, 2010; Zhou et al., 2022).

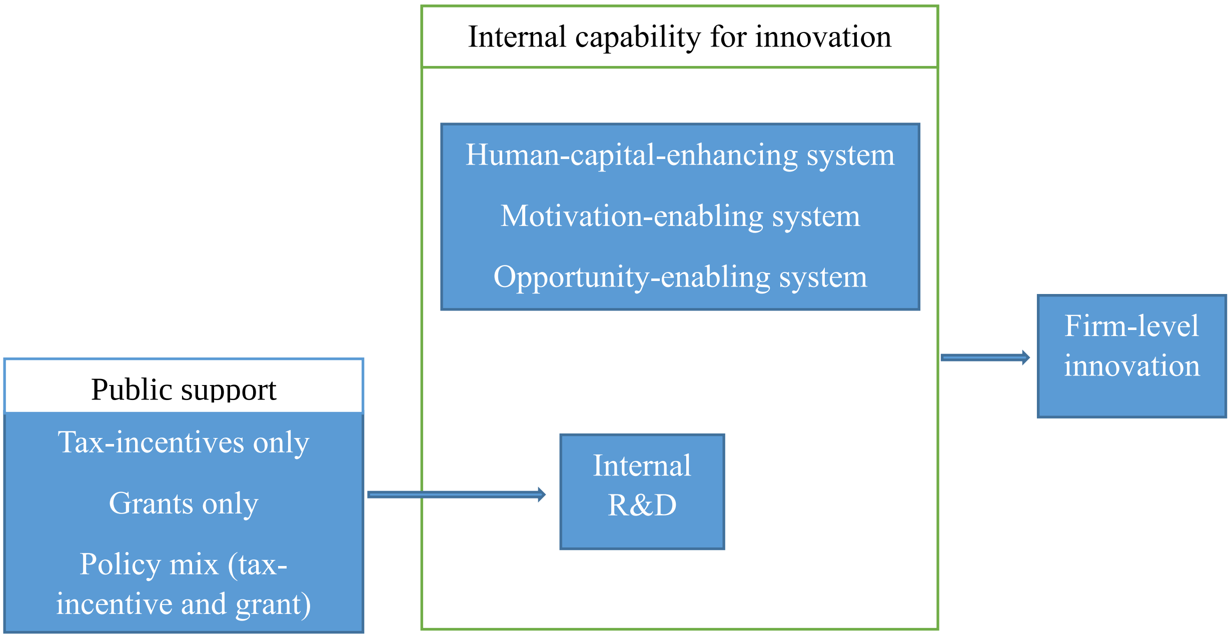

Figure 1.1: conceptual framework for HRM and public policy link with firm

Chapter 2

2 Policy mix: Evaluating the input additionality of public R&D Supports

Abstract

The study provides empirical evidence on the input additionality of public policy mix in the UK economy. While the individual impact of R&D grants and R&D tax incentives on business innovation input (e.g., R&D investment) has received considerable attention in the literature, the analysis of the impact of a mix of R&D grants and tax incentives, particularly as they apply to the UK economy is still limited. Our empirical evidence suggests that grants and tax incentives in isolation promote R&D investment in participating firms, although the effect is stronger for tax incentives than for grants. A mix of both also has a significant positive effect in firms – nonetheless, that positive effect is smaller when compared to that of tax incentives alone and stronger when compared to that of grants alone. This suggests that the effectiveness of the UK R&D tax credit is attenuated when used in combination with R&D grants. Exploring the policy support effects across different types of firms, we find that the effect of tax incentives alone on R&D is significantly stronger for small firms than for medium-large firms, and stronger for service firms than for manufacturing firms. Meanwhile, the policy mix effect on R&D investment is stronger for firms in the service, low-tech manufacturing, and Less-Knowledge-Intensive Service (LKIS) firms. This evidence has implication for policy design.

2.1 Introduction

Governments globally provide grants to private sector R&D through a wide range of policy schemes including direct R&D grants and indirect R&D tax incentives. Evidence from the European Commission (2017, p. 38) indicates that each of the individual policies has a significant impact on firms' private R&D investment. As policy instruments are never administered in isolation (Cunningham et al., 2013), firms often benefit from a mix of diverse policy instruments to support their R&D activities leading to interaction among the various support instruments. It is argued that the fact that the impact of individual policies within a mix is influenced by other instruments (Ringeling, 2005) precludes any comparative evaluation of instruments as if they were independent units (Flanagan et al., 2011). Many scholars including Guerzoni and Raiteri (2015), Radicic and Pugh (2016), and Lenihan and Mulligan (2018) have subsequently expressed concern about this gap in the policy studies literature regarding the role of policy mix in promoting business innovation and call for further investigations – thus the reason for this study.

The policy mix concept which, implies a focus on the interactions and interdependencies between different policies as they affect the extent to which intended policy outcomes are achieved (Flanagan et al., 2011, p. 702), is noted as receiving little attention primarily due to the lack of availability of datasets on innovation policy mix, thus making majority of empirical studies resort to individual instrument analysis (Guerzoni and Raiteri, 2015; Radicic and Pugh, 2016). Meanwhile policy evaluation scholars have cautioned that any analysis which relies on individual instrument risks attributing the influence of a policy mix on business innovation to one individual instrument in the mix. For instance, Guerzoni and Raiteri (2015) argue that the impact of a particular policy such as R&D grants on business innovative performance might be partially or even totally due to the influence of other policies such as R&D tax incentives, and that evaluating individual policies in isolation might lead to an overestimation of the individual policy impact in this case, R&D grants. The general argument in the literature is that, few research studies operationalise policy mix effects among firms primarily due to the lack of firm-level datasets which capture detailed information on the types of R&D supports that firms received (Radicic and Pugh, 2016; Lenihan and Mulligan, 2018). This has led to the recommendation by many scholars, including Rogge and Reichardt (2016) and those mentioned above that accessing datasets with a comprehensive information on the policy mix which businesses receive may present the greatest analytical advantage for empirical studies.

One important consideration on the part of policy makers is the issue of complementarity or substitutability between public R&D expenditures and firm-financed R&D investments. Policy makers concern themselves with the possibility that allocating public funds may substitute for investments that the firm would otherwise undertake in the absence of public support. Put differently, the government wants to avoid the scenario whereby public support "crowds out" private R&D, resulting in a less than desired social effect. A preferable scenario would be where public funds allocations complement or "crowd in" private R&D by supporting the projects that firms would otherwise not undertake. In short, policy makers will want to know whether public support creates an additionality effect by complementing private sector R&D efforts, or substitutes private sector R&D investments.

This study is further motivated by the fact that, first, the UK's public innovation support to businesses' innovation activities has increased tremendously over the past years. According to Vanino et al. (2019), the UK invests around £3bn annually in support of R&D, and innovation and this amount was set to increase to £5bn by 2020. In another report, over the 2012 to 2020 period, the UK increased its support for business R&D from 0.16% in 2012 to about 0.40% of GDP in 2020 ranking the UK third among OECD countries (i.e., behind France and Russia) that provide the largest level of government support (as a percentage of GDP) to business R&D (OECD March, 2023) (see Figure 1.2). Although the theoretical rationale for the UK government's decision to invest such great effort into private R&D is in response to market failure, market failure does not prescribe the exact manner in which intervention should be done. Direct R&D grant and R&D tax incentives are the main intervention instruments employed by industrialized economies around the world to provide an incentive for private sector investments in R&D. While both grants and tax incentives may complement each other, the mechanisms of their administration are different. Thus, an enquiry into the effectiveness of innovation policies mix in promoting firms' R&D is critical to understand whether mixing grants with tax incentives complements or crowds-out the effect of each other. Meanwhile, policy makers may want to know the extent to which policy goals are achieved, which may subsequently serve as a guide for future policy designs and decision making. Secondly, government worldwide including those in the OECD, EU and partner economies increasingly rely on direct grant support and tax incentives to promote business R&D and encourage economic growth, in compliance with international rule (OECD, 2014; Appelt et al., 2016). Also, the UK adheres to the EU State aid rule in administering R&D and innovation supports. While there are nuance differences at the granular level, at the nominal level, there are similarities among support schemes in terms of their designs and impact, particularly among the EU members countries (Lenihan, 2020). Thus, the UK's public support schemes for firm-level innovation are compatible with that of the other OECD, EU and partner economies, which implies that the finding on the impact of direct grant and tax incentive supports in the UK context is generalisable to the other OECD, EU and partner economies.

Direct government funding and tax support for business R&D, 2020
As percentage of GDP

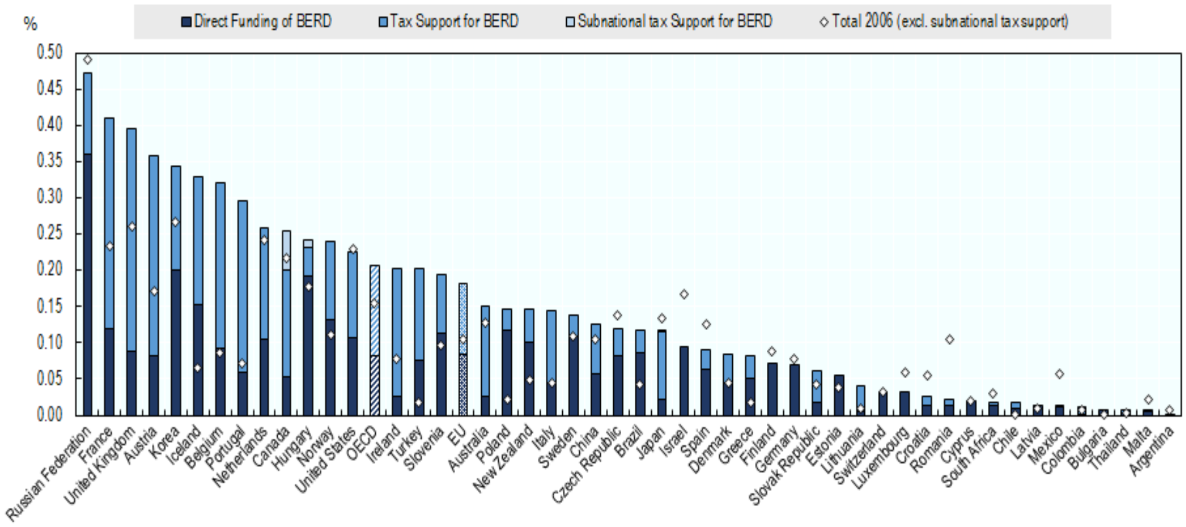

Figure 1.2: Government support for business R&D. * BERD (Business Expenditure on R&D). Adapted from OECD (2023): https://www.oecd.org/sti/rd-tax-stats.htm

The main econometric issue with the evaluation of the effect of public grant on the performance of recipient relative to non-recipient firms is the issue of selectivity and endogeneity. Since grant recipients are not randomly selected, recipient and non-recipient firms may differ substantially. In this situation, if the receipt of public support is related to some covariates that are correlated with performance but are not taken into account in the evaluation, then any potential policy effect being estimated in the evaluation may not necessarily reflect the true causal relationship between policy support and performance. In order to account for this issue, the current study uses coarsened exact matching with the propensity score matching technique, normally used in the program evaluation literature (e.g., Heckman et al., 1997; Guerzoni and Raiteri, 2015; Hünermund and Czarnitzki, 2019), in order to identify a valid control group for public support receiving observations. Information on public R&D supports is sourced from the UK innovation survey dataset to provide an evaluation of the effectiveness of direct R&D grants and indirect R&D tax incentives in promoting participating firms' propensity to invest in R&D. Specifically, the study's evaluation is based on the potential R&D input additionality of a mix of grant and tax incentives, as well as the additionalities of the individual instruments in isolation. By doing so, the study contributes to the literature by providing an empirical application of the policy mix concept proposed by Rogge and Reicharct (2015), and documents a complementary relationship between public support and private R&D investment. Second, we offer a deeper understanding of the link between public support and private R&D investment by providing evidence of the effectiveness of a mix of R&D grant and R&D tax incentives as well as that of the individual policies in isolation, and thus contribute to the limited literature on the link between policy mix and firm innovation input. This also extends the literature which often focuses on evaluating the impact of individual policies. A novel contribution of this study is the fact that it derives more substantiated policy recommendations grounded in better understanding of how different types of firms may respond differently to similar policy initiatives. Although few studies have examined the impact of tax credits for specific types of firms along dimensions of industry and size (e.g., Castellacci and Lie, 2015; Freitas et al., 2017), no study, to the best of our knowledge, has examined policy implications for multiple firm-specific contexts. This study therefore extends the current literature by providing a comprehensive evaluation of the input additionality impact of tax-incentives-only, grants only and policy mix across dimensions of industries, firm sizes, firm knowledge and technology intensity level, and firm productivity level. This might ultimately inform how the R&D performance of specific firms could be enhanced to attain greater knowledge creation and social return.

The remainder of chapter two is structured as follows. Section 2 presents the research conceptual framework, explaining how tax incentives or grants in isolation, and their interaction can influence R&D investment. Section 3 presents the related literature and hypotheses formulation. The econometric method used in this chapter is explained in Section 4. The data and descriptive analysis of variables are presented in Section 5. Section 6 presents the empirical results, detailing the policy impact for the full sample and across multiple dimensions of firm specificity. The chapter's conclusions and discussion of key findings are presented in Section 7. Limitations and avenues for future research are in Section 9.

2.2 Conceptual background

In taking an economic approach to firm-level innovation which suggest innovation is complex and subject to market failures (Arrow, 1962; Bryan and Williams, 2021). Firms' innovation decisions and behaviour are guided by many factors, including investment opportunities in the marketplace, the market incentives for innovation, firm's own resources for innovation, the expected rate of return on investment and firms' own required/hurdle rate of return. Some of these factors have underlying constraining factors including risk and uncertainties, imperfect information, and issues of appropriability externalities of technological knowledge, which prevent the firm from optimally allocating resources to innovation activities (Nelson, 1987; Arrow, 1962). In the first instance, the market on its own is generally inefficient in providing adequate incentives to induce innovation by profit maximising firms. The general reasons why market incentive mechanisms are likely to be inefficient in producing the socially optimal rate and direction of innovative activities are grounded on the economic distinctiveness of knowledge and its creation (Weber and Rohracher, 2012; Vanino et al., 2019). In brief, knowledge creation is characterised by indivisibilities, by uncertainty, by public good dimensions, and by appropriability externalities (Lipsey and Carlaw, 1998). On the one hand, imperfect information and inefficiency of the capital markets result in the firm's inability to borrow whatever amount is necessary to finance its R&D activities In fact, it is asymmetric information about uncertain prospects of innovation activities which creates the problem of moral hazard and adverse selection, making it difficult for the capital market to behave in an efficient manner, which forces firms to fund R&D from internally generated resources (Jadiyappa et al., 2023).

Secondly, firms are not fully informed about opportunities available in the marketplace, in respect of new technologies and the potential positive effects which the new technologies might have. Firms can only allocate resources efficiently if they are well informed about available opportunities and the likely consequence of their decisions. However, the market often lacks the necessary information, particularly in respect of new technologies that the firm could explore. Even in a situation where full information regarding a new technology is available, the market mechanism which might provide this information may be inadequately developed. The lack of adequate information creates uncertainties around new technologies, which might subsequently lead to the firm miscalculating the risk and return associated with the technology. There is also the issue of the market demand level for the firm's R&D output, which is mostly difficult to estimate, especially if the firm seeks new-to-the-market innovation. Estimating the market demand for its output might not be too difficult if the firm seeks incremental innovation since it might have a fair idea of the output demand level. Nonetheless, the firm's decision to invest in R&D and/or increase the level of its investment will depend on the expected scale of market demand for the R&D output. The firm's R&D investment will be greater if both the initial scale of the market demand and its expected rate of growth are greater. In other words, if the expected gain in profit accruing to the firm due to the innovation is lower, then the firm will not innovate.

Finally, firms' innovation decision in terms of any specific R&D project will be guided by the relative rates of return compared to other projects and the firm's hurdle rate of return from investment. Assuming a firm has a portfolio of potential innovation projects to choose from, it is expected that the firm will first rank the projects in order of their respective expected rate of return, and therefore commit investment beginning from the project with the highest expected rate of return down to the project with the least rate of return. It is also expected that the firm will decide on a hurdle rate of return that it is prepared to commit investment to, so that only projects with expected rate of return exceeding the hurdle rate get funded by the firm.

Public supports impact firms' R&D efforts by influencing the above-mentioned economic and market factors which influence firms' decisions to engage in R&D or increase their R&D efforts. For instance, riskier projects are typically associated with higher hurdle rates, hence public funding to the firm has lowers the firm's hurdle rate through its direct effect of reduced risk of R&D to the firm, thereby rendering projects which were initially marginal become non-marginal and are undertaken. For instance, if based on its projects ranking and hurdle rate the firm decides to commit investment to only two out of six projects, then any public support has the effect of lowering the firm's hurdle rate so that projects which were initially below and now are above the hurdle rate are undertaken. Exploring the possible ways by which public support interacts with the different market factors that determine firms' innovation decisions may help with our understanding of the innovation behaviour mechanisms of the firm in terms of the level of investment a firm decides to commit to innovation as well as the nature of innovation. In the next few sections, we provide a detailed description of these possibilities, starting with direct grants.

2.2.1 R&D direct subsidies

Here we explore the possible behavioural effects that direct subsidies to R&D (i.e, grant funding) might have on a firm. This leads us to a discussion of the particular characteristics of grant support and how those characteristics may influence a firm's innovative behaviour by influencing the economic factors that determine its decision to invest in R&D. Generally, a firm faces and chooses the most profitable alternative from a collection of several innovation opportunities available in the marketplace based on their associated cost, risk and returns. This means that the firm might try to choose its R&D effort and return levels to jointly maximise the present value of its profit. Understanding how public supports interact with the different market factors that determine a firm's innovation decision may help with our understanding of the innovation behaviour mechanisms of the firm in terms of the level of investment the firm decides to commit to innovation, as well as the nature of innovation.

We begin by establishing the fact that a grant is normally given at a percentage of the total cost of the R&D project. This means it reduces the marginal cost of the project in the proportion of the said percentage and can have a direct effect of inducing the firm to do a greater volume of investment (which equals the total of the firm's own funds and the grant given). The R&D cost-sharing attribute of grants also implies a reduction in the risk of R&D to the firm which might induce the firm to take on projects that are more marginal than otherwise (assuming that there is a ranking of investment possibilities that are eligible for grant funding). Now, suppose that a firm wants to make investment allocation decision across a portfolio of potential projects with different risk and return, a grant is likely to mean that some eligible projects move from below to above the firm's hurdle rate of return. This will mean that the firm expends greater total research effort. Also, since grant funding is often given for some specific project and not all projects in the firm's innovation portfolio will mean that the funded project moves up the projects ranking causing a distortion in the relative risk and return of projects in the firm's portfolio. This may mean a project that was not initially ranked as the most profitable could potentially move to the top of the ranks and gets executed first because it got grant support. This is to say that project selectivity relating to a grant committee's interest in, or bias towards a particular project, or even funding eligibility criteria, can potentially distort the firm's project ordering and thus which projects get done. Now, these selectivity decisions on the part of the funding committee or even grant eligibility conditions might also exert a qualitative effect where a grant might alter the nature of firms' R&D investment (Appelt et al., 2016). In the UK for instance, because most of Innovate UK's grants are particularly oriented towards new products rather than processes, firms' R&D investments may be directed more to product rather that process related change.

Grant funding is also associated with a signalling benefit (Spence, 1973). Winning a grant out of a competition serves as a signal to other potential investors about the quality of the project and innovative capability of the firm. This reduces the problem of information asymmetry and moral hazard on the part of the firm. Firms might therefore use subsidized projects as a signalling mechanism in order to obtain complementary or future financing from the capital market (Connelly et al., 2011; Bianchi et al., 2019). For instance, a project which is 50% financed by a grant may be helpful in signalling the quality of the project to obtain other sources of financing from the private sector (Busenitz et al., 2005). Research evidence suggests that it is easier for firms who have been awarded grant support in the past to access further grant support and follow-on equity investment (Antonelli and Crespi, 2013). The consequences of which is a potential boost in the firm's liquidity to do more R&D. For example, it might be that once a firm is able to secure SMART funding from Innovate UK, it serves as a signal in obtaining an equity finance. This signalling benefit could particularly transition a financially constraint firm that could otherwise not be able to undertake any feasible and profitable projects into an R&D performer. Meanwhile, there is also the possibility that this signalling benefit might exacerbate the distortionary effect of grants described above, where in this case due to a selection effect and eligibility criteria a particular project gets funded out of a portfolio rather than perhaps a better project. In this situation, a grant will potentially be sending the wrong signal in terms of portraying that project as a 'great project' thereby attracting other funds from the capital market. Although it benefits the firm since the signalling brings in capital, not so much benefit will accrue to the market if the 'wrong project' was indeed selected and implemented instead of perhaps other project with relatively more profitable social return[1].

If the level of R&D input is directly related to the quality of R&D output/return, then grant support would generate an increase in the firm's private R&D investment in response to an induced increase in R&D returns which accrue to the firm (OR in response to higher R&D productivity resulting from increase R&D returns that accrue to the firm). That is, grant funding enables the firm to initially operate at a higher R&D input level (while still keeping its own share of the R&D cost at a constant level), potentially creating a superior output return than what the firm could have realised with only its private R&D input level. Typically, a firm will always try to choose both R&D input cost and R&D output return levels to maximise its private profit This that any developed superior technology which should have been associated with a higher private input cost, is now associated with a lower private input cost in the post grant era, creating in an increase in the firm's marginal productivity of R&D. This increase in R&D marginal productivity induces the firm to increase its private investment in R&D: The additionality effect resulting from the indirect effect of the grant funding.

[1] Unlike profit maximising firms, policy makers are often interested in funding projects with high social return. Externalities from knowledge mean that private return and social return will differ (Griliches, 1958)

Suffice to say, there are costs and uncertainties associated with getting public grants. That is, getting an R&D grant for a project is somewhat unpredictable as the firm will need to engage in a competition for the grant funding. Second, grant funding is often given once and for specific innovation projects, or it might only cover certain aspects of the innovation cost due to eligibility conditions. This means that once that subsidized project is complete the firm returns to having the normal cost of capital available in the marketplace for investment. These facts may indicate that the firm cannot rely on grant funding to make long-term R&D financing decisions. This may result in the firm selecting and investing in low-risk projects or investing in projects with short-term returns.

In summary, as much as a grant has additionality effects in terms of the quantity of R&D investment done by firms, it might also exert a qualitative effect where the grant changes the nature of firms' R&D investments due to grant eligibility conditions. Grants may also distort the relative return of projects in a firm's R&D portfolio, and they can be used by firms as a signal of quality to obtain funds from the capital market. This signalling benefit might either leverage the distortionary effect of the grant or potentially exacerbate the problem. Nonetheless, the reduction in cost and risk of R&D together with the signalling advantage enable the firm to invest more in R&D.

2.2.2 R&D tax incentives

Similar to the preceding section, this section explores how the characteristics of R&D tax incentives influence a firm's project selection and R&D investment decision. We begin by establishing the fact that a profit tax has a distortionary effect, increasing the product price comparative to the no tax situation. Consequently, there is an extra burden of taxation in depressing the marginal profitability of a firm's innovations, therefore reducing the incentive to employ all input including R&D input. Like grants, tax allowances and tax credits for eligible R&D investment have the direct effect of reducing the marginal cost of R&D and an indirect effect of inducing more R&D investment through the effect of a lower cost of private R&D input. Tax incentives provide beneficiary firms with the opportunity to overcome liquidity constraints, allowing them to undertake projects at the margin of their portfolio. Nonetheless, unlike grants, tax incentives are neutral in terms of the activity and content of the R&D project being supported, meaning that they can cover not just one project but the entire portfolio of projects once the R&D investment in which the firm has already done meets the eligibility criteria (OECD, 2014; Appelt et al., 2016). This means that the firm will select and invest in projects in the order of which offers the greatest private return. In contrast to grants, tax incentives offer no signalling benefit since the latter is available to all firms with eligible R&D expenditure. Also, the distortionary effect commonly associated with grant funding is not found with tax incentives since the funding goes for all eligible R&D investments relating to projects in a firm's portfolio. They however provide a drop in the hurdle rate of return allowing firm to expense greater volume of R&D as more projects move from below to above the hurdle rate of return. One advantage of tax incentives relative to grants is that tax incentives minimise the discretionary decisions involved in project selection for grant funding. Their accessibility is quite predictable in the sense that once the eligibility criteria is met funding is certain (Lokshin and Mohnen, 2012; Appelt et al., 2016). This means that their impact on the cost of innovation is quite predictable. Most tax incentive instrument schemes run for a long period of time and therefore provide a reliable base for long-term financial planning and R&D decisions (Appelt et al., 2016). We can therefore assume that the assurance of access to continuing finance towards all eligible R&D investments may not only induce firms to undertake more R&D but also to engage in a continuous investment in R&D activities and potentially long a payback period. This ease of accessibility as well as their reliability could increase the probability of a non-R&D performing firm engaging in R&D.

Obviously, besides the no-distortionary, no-signalling benefit and market neutral effects that are particular to a tax incentive, this policy tool shares many attributes with a grant including R&D cost reduction and a liquidity effect which can induce the firm to expense a greater volume of R&D.

2.2.3 Policy mix

In the previous two section, we looked at various characteristics of grant and tax incentives and how they individually impact the R&D investment decision of the firm. This section focuses on how the interaction of the effects of both tax and grant may impact the innovative behaviour of a firm. It is generally understood that the way in which policy instrument impacts the innovation behaviour of firms is connected to the ways in which other conditions and instruments influence the same target firms. The "policy mix" concept acknowledges that policy instruments may interact with the portfolio of already existing instruments for a given target group or technology. Central to the policy mix concept are the interactions among the policy instruments which imply that the impact of an individual policy instrument is influenced by the coexistence of other instruments (Rogge and Reichardt, 2016). The interdependencies of influence emanating from the direct and indirect operations and outcomes of policy instruments essentially impact the overall effect of the instrument mix and thus the attainment of policy objectives (Flanagan et al., 2011). The over-all effect could be complementary, substitutionary or neutral depending on the degree of consistency among the effects of the individual policy tools.

The question put forth in this current study is, does a mix of the tax incentive and direct grant schemes result in an enhanced additionality effect of the individual schemes? Put differently, will the effect of the two instruments reinforce, contradict or weaken each other's effect through contamination? It can be said that the strategic combination of a direct grant and tax incentives will present an effective mix of complementary instrument effects. Complementary supports in a mix permits the likelihood of a successful R&D outcome by developing the capacity of the target firm to capitalize on all aspects of the supported project and to build up capabilities to be used in other and future projects (Cunningham et al., 2013). In other words, participation in a mix of a tax incentive and an R&D grant will increase participating firms' private R&D investment more than firms that do not receive any support or use either of the supports in isolation. The intuition for such a treatment effect is as follows: tax incentives are non-competitive and designed to reduce the cost of R&D for all firms that engage in R&D activities, and thus provide liquidity for the focal firm. Although competitive and generally targeted towards reducing the cost of long-term projects with higher knowledge spillover effects, grants support also provides liquidity for the focal firm. A combination of a tax incentive and a grant would mean that the firm could potentially direct the financial resource freed up by the former towards projects supported by the latter. Thus, the tax incentives may create a financial avenue for additional experimentation in the subsidized R&D activities that the firm would otherwise not have undertaken. Similarly, since both tools lower the hurdle rate of return through reduced R&D cost and risk to the firm, the firm could potentially use the tax credit and any fund sourced externally to commit to projects whose rate of return may have moved from below to above the firm's hurdle rate of return. The combined effect of both public supports is the potential to induce the firm to invest in new R&D projects that would not have started otherwise or hire new R&D personnel that it would not have hired otherwise - an investment which may lead to the generation of new knowledge, skills and capabilities, which may subsequently result in an innovation outcome.

Obviously, we would expect a mix of a grant and a tax incentive to exhibit the advantages as well as the disadvantages of both policy instruments. For instance, we would expect higher additionality on a firm's R&D investment since the firm gets more financial support by accessing both support tools. The implication is first and foremost an expectation of an additionality effect of policy mixes on the R&D investment of participating firms when compared with firms which receive no public support. Secondly, additional to the potentially enhanced additionality effect (i.e., the combined additionalities of a grant and tax incentive), we would also expect a leveraging effect between the distortionary and signalling effects of a grant, while the market neutrality of a tax incentive allows the firm to take on more projects than otherwise – thus, having both supports will induce a firm to invest more in R&D than having either supports in isolation.

2.3 Input additionalities of public support: Hypothesis development

2.3.1 Additionalities of direct R&D subsidies

Several studies have evaluated the input additionality effect of direct R&D grants. The central question that researchers ask is whether grants crowd-out firms' private innovation efforts, or provide an additionality effect and thus advance their upsurge due to some complementary relationship between them (David et al., 2000; Guerzoni and Raiteri, 2015; Radicic and Pugh, 2016; Marino et al., 2016). The argument regarding the substitutability, additionality or complementarity as pertaining to public grant funding and firms' private R&D efforts has long been debated in the literature. Although most studies seem to reject the presence of a full crowding-out effect, the results are ambiguous: while Czarnitzki and Fier (2002), Almus and Czarnitzki (2003), and Herrera and Sánchez-González (2013) find no evidence of a full crowding-out effect, Wallsten (2000), Busom (2000), and Lach (2002) find indications of partial substitution of private R&D and innovation investments with public funding. In the same spirit, David et al. (2000) survey 33 pre-2000 empirical studies on public support impact and found 16 studies reporting a complementarity effect, 11 studies reporting a substitution effect, 3 mixed results and 3 insignificant results. According to the authors, the US based studies tend to find more substitution effects than non-US based studies. Zúñiga-Vicente et al. (2014) also reviewed 77 pre-2011 empirical studies on the effect of public R&D grants on firms' private R&D investment and reported mixed and inconclusive results for which the authors argued could not be completely ascribed to methodological differences. Zúñiga-

Vicente et al. (2014) particularly found that about 48 of the studies across various levels of aggregation find public grants provided additionality effect to private R&D investment, 15 studies reporting a substitution effect and 14 studies reporting insignificant results. A recent meta-regression analysis of 12 tax credit and 25 grant studies on R&D investment additionality by Dimos et al. (2022) reports 55.6% (36% and 8.4%) of 347 recorded grant effects are additionality (no effect and crowding out) and 57.4% (41.8% and 0.8%) of 251 recorded tax credit effects are additionality (no effect and crowding out). Marino et al. (2016) examined the R&D expenditure of French firms for the 1993-2009 period and found that firms that benefited from a grant in isolation on average invested 39-67 percentage points more than the control group of firms that did not receive any public funding, that is a reduction in the R&D input additionality when grants interact with tax credits. Görg and Strobl (2007) also provide evidence which suggests that R&D input additionality decreases by grant size. Görg and Strobl (2007) specifically estimate the differentiating effects of grant size on Irish manufacturing firms and show that while small grants induce an additionality effect, large grants crowd-out domestic firms' private R&D investments. In the same spirit, Guellec and de la Potterie (2000) found an inverted U-shaped relationship between public subsidies and private R&D spending. Czarnitzki and Hussinger (2018) analysed the effects of public R&D funding on R&D spending and the subsequent effect on the patenting behaviour of German firms. The authors found that public R&D grants do not only induce additional R&D spending in subsidised firms (37% more than in non-subsidized firms), but also accelerate their R&D spending (27% more than in non-subsidized firms). Thereafter, the induced additional R&D spending subsequently led to a 6.6% increase in patenting and a 9.0% increase in patent quality. Based on our conceptual framework and the reviewed empirical studies, we hypothesis that:

2.H1: Grant in isolation will generate additionality effect on the R&D investment of participating firms in comparison to firms that receive no funding.

2.3.2 Additionalities of R&D tax incentives

Most studies that have evaluated the input additionality impact of R&D tax incentives found evidence of a positive and significant impact, although the magnitude of the positive input effect differs depending on the country, the period considered, and the econometric method applied. Hall and van Reenen (2000) reviewed the econometric evidence on the effectiveness of fiscal incentives for OECD countries' R&D activities and found evidence that suggests that, on average, a dollar in tax credit for R&D stimulates a dollar of additional R&D spending. Using a matching procedure, Sterlacchini and Venturini (2019) consider the impact of tax incentives on the R&D of manufacturing firms based in France, Italy, Spain and the UK, over the 2007 – 2009 period and find significant increase in R&D intensity in all countries except for Spain. This effect is however driven only by the behaviour of small firms – the authors noted. Their benefit-cost ratio analysis of R&D tax policies revealed evidence of substantial additionality effects in Italy and the UK. Guceri (2018) also found that the UK's R&D tax policy reform which changed the definition of an SME from less than 250 employees to less than 500 employees lead to an increase in beneficiary firms' R&D spending and employments of R&D staff, which translates to a user cost elasticity between -0.88 and -1.18. Guceri (2018) also noted that the additional R&D generated through the tax relief was entirely due to an increase in the number of R&D employees in the companies' workforce. Additionally, tax incentives may not only encourage non-R&D firms to enter R&D and but to continue engaging in R&D activities – this is empirically evidenced by Arque-Castells and Mohnen (2011) study, which evaluated the effectiveness of Spanish R&D tax credit on firms' decisions to enter R&D and to continue R&D activities irrespective of the future development of the tax system. The authors found that 12% of firms entered R&D because of the tax credit, and 13% continued to invest in R&D. We therefore hypothesize that:

2.H2: Tax incentives in isolation will generate additionality effect on the R&D investment of participating firms in comparison to firms that receive no funding.

2.3.3 Additionalities of public policy mix

As mentioned in the earlier sections, an evaluation of the R&D impact of public policy mix is limited particularly regarding the UK economy. A recent study on the policy mix additionality effect was conducted by Guerzoni and Raiteri (2015). The authors analysis of the 27-member states of the EU, Norway and Switzerland economies finds a positive and significant effect of a mix of tax credit and grants on participating firms' private expenses in innovation activities. Specifically, there is a 9.3 percentage points more mix recipients increasing their private R&D spending than the non-subsidised control group. However, for recipients of a tax credit only and a grant only, there were respectively 2.9 and 5.3 percentage points more subsidised firms increasing their private spending than non-subsidized firms. Radas et al. (2015) find similar results to that of Guerzoni and Raiteri (2015). According to Radas and colleagues' study on

175 SMEs in Croatia, direct R&D grants alone or a mix with R&D tax incentives strengthens SMEs innovation activities in terms of R&D collaboration, R&D intensity and employment. Applying a combination of difference-in-difference with propensity scores and exact matching techniques on 1993-2009 panel data of 12,169 French businesses, Marino et al. (2016) find evidence which suggests that while the R&D investment of firms that benefited from a grant only was on average 39 percentage points more than the control group of firms that did not receive any public funding, the R&D additionality effect was only 23 percentage points more for firms which benefited from a mix of grants and tax credits in comparison to the control group. The authors also recorded significant substitution of private R&D investment with public R&D funds, especially for businesses that receive medium to high value of public grants. Dumont's (2017) study on 5634 Belgian businesses finds similar results. Using 2003-2011 data and applying a fixed effects econometrics technique, Dumont (2017) finds that all the possible mixes of R&D grants with six different R&D tax credits have either ineffective or a negative effect on R&D intensity. The diminishing effect of the policy mixes is found to be particularly so for businesses which combine R&D grants with several R&D tax benefits. Dumont (2017) also finds that the impact of public support on R&D intensity is dependent on the econometric specification and evaluation technique considered. The policy mix studies reviewed so far seem to indicate that the policy mix effect on innovation input may either be stronger or weaker in comparison to the use of individual instruments. Thus, based on our conceptual framework and the empirical literature reviewed we put forth the following hypotheses:

2.H3: *A mix of tax incentive and direct grant will generate additionality effect on the R&D of participating firms in comparison to firms that receive no funding.*

2.H4: *A mix of tax incentive and direct grant will generate a stronger additionality effect on R&D than the additionality effects in 2.H1 and 2.H2.*

2.4 Econometric method

The current study seeks answer to the question, what would have happened to firms' private R&D investment if they had not received public support? In a randomized experiment, the outcomes in treatment and control groups may often be compared directly because the observations are likely to be similar (Rosenbaum and Rubin, 1983). However, in an observational dataset, such as one resulting from policy intervention, there is the issue of possible endogeneity and selection biases associated with allocation decisions of funding agencies and self-selection of businesses into support programmes. This implies a direct comparison of outcomes of treatment and control firms may be misleading since there may be systematic differences between firms that are exposed to treatment and those that are not. Consequently, one cannot use the average outcome on all the non-treated firms to estimate the counterfactual effect.

2.4.1 The sample selection problem

As mentioned in the introduction and the preceding paragraph, a key analytical component in this study is how to deal with the problem of sample selection bias. One option would be the use of a good instrument to employ an instrumental variables estimator appropriate for this study's context of additionality in firm R&D investment. Nonetheless, it is difficult to find and justify convincing instruments, and the data we have is no exception to this. Several other estimation techniques have been adopted in the econometric evaluation literature to cater for this analytical drawback. These among others include difference-in-difference estimation, regression discontinuity design estimation (e.g., Bronzini and Piselli, 2016), fixed effect estimation and non-parametric matching estimation. Like the many other procedures used by studies on policy impacts, none of the above-mentioned estimation techniques has been noted to provide undisputed results. In line with the recommendation of scholars including Caliendo and Kopeinig (2008), Guerzoni and Raiteri (2015), and Vanino et al. (2019), this study employs the use of a propensity score matching technique to overcome the issue of selection biases associated with allocation decisions of funding agencies and self-selection of businesses into support programmes. The rationale of the matching is to create a suitable control group of non-treated firms which is similar to the treated firms in all relevant pre-treatment characteristics which influence the likelihood of receiving the treatment, and then use that control group to estimate the non-observable counterfactual (Caliendo and Kopeinig, 2008; Guerzoni and Raiteri, 2015). An advantage of the propensity scores matching methodology, like other matching methods, is that it requires no assumptions about functional forms and distributions of the error term. The downside, however, is that it only controls for the selection on observables. Thus, the researcher needs to maintain the assumption that all the important characteristics driving selection into treatment are observed.

It suffices to note that the general modelling problem is the estimation of the causal effect of public support on a firm's probability of investing in $R\&D$. Let $TREAT_i \in \{0, 1\}$ be an indicator of whether or not a firm received public support, and let $R\&D_i^1$ be the R&D probability outcome of the firm if it received support. Also denote by $R\&D_i^0$ the R&D probability outcome of the firm *had it not received any public support*. The causal effect of the receipt of public support for firm i is then defined as

$$R\&D_i^1 - R\&D_i^0 \quad (1)$$

The fundamental problem of causal inferences is that the quantity $R\&D_i^0$ is unobservable. That is, the analysis can be viewed as fronting a data-missing problem. Following the microeconometric evaluation literature (e.g., Heckman et al., 1997; Guerzoni and Raiteri, 2015), this study defines the average treatment effect of public support on the firms receiving public support as

$$\alpha^{TT} = E\{R\&D_i^1 - R\&D_i^0 | TREAT_i = 1\} = E\{R\&D_i^1 | TREAT_i = 1\} - E\{R\&D_i^0 | TREAT_i = 1\} \quad (2)$$

Causal inference depends on constructing a counterfactual for the last term in Equation (2), which is the outcome the support-receiving firms would have experienced, on average, in the absence of the support. This is estimated by the R&D performance of the control group of firms that did not receive any support. That is,

$$E\{R\&D_i^0 \middle| TREAT_i = 0\} \quad (3)$$

The estimation of Equation (3) is confronted with the problem of selectivity. If the receipt of public support is correlated with a number of observable covariates X but Equation (3) was estimated as the average for all non-treated firms, then a biased estimate would be obtained. It is therefore crucial that a valid counterfactual that avoids the problem of selectivity is constructed for the analysis. Put differently, Equation (3) should be estimated using a group of non-treated firms that are similar to the treated firms in terms of the observable covariates. Now, with a vector of observable covariates X at hand, there are two important assumptions necessary to achieve an unbiased estimate of the true treatment effect (see Caliendo and Kopeinig, 2008). First, there is the need for a region of overlap (a.k.a., the common support assumption) between the treated and control group such that $0 < P(TREAT = 1|X) < 1$, that is, ruling out the perfect predictability of TREAT given X (see Hackman et al., 1997). The second assumption necessary for Equation (3) to be an unbiased estimate of the true treatment effect is that of conditional independence assumption introduced by Rubin (1977). According to the conditional independence assumption, potential outcomes (in our case propensity to invest in R&D) are independent of selection into treatment given a set of observable covariates X which are not affected by the treatment. Practically, the conditional independence assumption permits the researcher to assume that selection into treatment is based solely on observable characteristics and that all factors that determine treatment and the outcome of interest simultaneously are observable. Based on this, the researcher can then employ matching methods to pair treated with non-treated which are as similar as possible on the observable characteristics X and use the latter group to estimate the counterfactual scenario, $E\{R\&D_i^0 \middle| TREAT_i = 1\}$. That is, if the conditional independence assumption holds, then

$$E\{R\&D_i^0 \middle| TREAT_i = 1, X\} = E\{R\&D_i^0 \middle| TREAT_i = 0, X\} \quad (4)$$

And the average effect of public support on the treated firms is estimated as

$$\alpha^{TT} = E\{R\&D_i^1 \middle| TREAT_i = 1, X = x\} - E\{R\&D_i^0 \middle| TREAT_i = 0, X = x\} \quad (5)$$

2.4.2 The common support and conditional independence assumptions

The propensity scores matching methodology ensures that the common support assumption is satisfied. This matching approach entails pairing each treated firm with a non-treated firm using similar pre-treatment characteristics in such a way that the R&D performance of the non-treated firms can be studied to generate the counterfactual for the treated firms. Now, since matching involves comparing treated and non-treated firms across a number of observable covariates (e.g., employment, size, collaboration, skills level, regional and industry characteristics etc.), exact matching along each of these dimensions becomes impossible when dealing with so many covariates. That is, this study is confronted with the "curse of dimensionality". It is thus desirable to match the treated and non-treated on the basis of a single index that captures all the information from those covariates. Following the suggestion of Rosenbaum and Rubin (1983), this study uses the probability of receiving public support, conditional on firm specific characteristics to reduce the problem of dimensionality, so that a direct comparison between the treatment group and the control group may be more meaningful. Moreover, the propensity score estimation process allows the samples of treated and non-treated to be restricted to a common support by calculating the minimum and the maximum of the propensity scores of the potential control group and deleting observations on the treated group with probabilities smaller than the minimum and larger than the maximum in the potential control group.

Consequently, the study first estimates the probability of receiving public support (i.e., the 'propensity score') using a logit model where firm specific characteristics including employment, size, collaboration, skills level, regional and industry characteristics are used as controls (full list and description of all control variables is provided in section 2.5.3 below).

Now define P_i to denote the predicted probability of receiving public support for firm *i* (which is an actual support receiver). A non-treated firm j, which is the nearest neighbour in terms of its 'propensity score' (i.e., P_j) to the treated firm i, is selected as a match for firm *i* using the 'caliper' matching method. More formally, for each treated firm i, a non-treated firm j is selected such that

$$\tau > \left|P_i - P_j\right| = \min_{j \in \{no\ support\}} \{\left|P_i - P_j\right|\} \tag{6}$$

Where τ is a pre-specified scaler, known as the caliper and reflects the similarity of the propensity score between a treated and matched control group firm[2]. Matching is done with replacement, so that each observation in the non-treated control group can be used as a match multiple times.

[2] Here, since the dependent variable is dichotomous, for each policy intervention, the chosen caliper is calculated as 20% of the standard deviation of the respective estimated propensity scores (Austin, 2011).

In order to ensure unbiased estimates of the true effect of public support, this study also ensured the arguably strong conditional independence assumption is satisfied with the application of the matching estimator. Fortunately, the UK innovation survey used by this study provides a rich data on a wide variety of firm specific characteristics which allowed the study to construct variables that can be argued to capture any non-random selection into treatment.

Apart from ensuring that both the common support and the conditional independence assumption are satisfied, this study also ensured that the propensity scores have a similar distribution ("balance") in the treated and control group. Balance in individual covariates across treatment and control groups (Austin, 2009) were also ensured before finally conducting the ATT estimation. Standard errors were clustered following Abadie and Imbens (2016) methodology for the nearest-neighbour matching procedure to account for the additional source of variability introduced by the estimation of the propensity score (Heckman et al., 1997). Finally, as a robustness check, this study relied on kernel matching technique with a bandwidth of 0.05 to test the sensitivity of the propensity score matching method.

It is worth noting that, before estimating the probability of receiving public support (i.e., the propensity score) and the subsequent matching, some of the covariates were coarsened for the purpose of matching. As suggested by Iacus et al. (2012), the aim of this process is to improve the balance of matched samples and the quality of the inferences drawn from the propensity score matching. Accordingly, the study temporarily coarsened covariates including degree dummy, export dummy, year of funding dummy, region of firm location and 13 sector dummies of two-digit classification. Next, observations were sorted into strata, each of which has the same values of the coarsened variables. Next, the observations in any stratum that do not include at least one treated and one control observation were pruned from the dataset. Only the observations within a stratum containing both a treated and a control unit were then kept. Subsequently, estimation of the probability of any firm participating in public funding was carried out based on a set of relevant observable characteristics which have been found to influence the likelihood of public fund participation in the previous literature.

2.5 Data and variables

2.5.1 The data

The data used for this analysis is obtained from the UK Innovation Survey (UKIS) complemented by the Business Structure Database (BSD). Precisely, the data comprises of the

UKIS 2015 covering the years 2012-2014, UKIS 2017 covering 2014-2016 and UKIS 2019 covering 2016-2018 merged with the BSD[3]. The UKIS database provides information on whether a firm received innovation support in the forms of a tax incentive or a direct grant during the survey period. The data also provides information on firms' collaborations with external bodies and on firms' exporting. The BDS on the other hand provides detailed information on firm-level characteristics such as employment and turnover. Our sample consists of innovative as well as non-innovative firms and covers firms with 10 or more employees and in all industries.

Table 2.1 presents the descriptive statistics of the variables used in our analysis. In total, the sample consist of 42,323 observations with 22% of them being R&D performers. Meanwhile, 40,062 out of the total sample received no public support representing (94.66%), 1,390 (3.28%) received tax incentives only, 379 (0.90%) firms received grant only and the remaining 492 (1.16%) firms received both tax and grant supports from the UK government. These statistics indicate firms that do not receive any government support to be the largest group. The possible explanation to this could be the fact that most R&Ds performed in firms are either not eligible for tax benefits or the fact that a considerable share of R&D-active firms simply do not apply for any public funding.

[3] The UK Innovation Survey, UKIS 2015 (UKIS 2017 and UKIS 2019) sampled 29,732 (30,479 and 30,492) UK enterprises with ten or more employees, and had a response rate of 51% (43% and 45%)

Table 2.1
Descriptive statistics across treatment participation

	Full Sample			No support (0/1)			Tax incentives only (0/1)			Grant only (0/1)			Both tax and grant (0/1)		
	# firms	Mean	SD	# firms	Mean	SD	# firms	Mean	SD	# firms	Mean	SD	# firms	Mean	SD
Internal R&D (0/1)	42,323	0.215	0.411	40,062	0.178	0.383	1,390	0.906	0.292	379	0.633	0.483	492	0.959	0.198
Employment (log)	42,323	4.182	1.478	40,062	4.174	1.481	1,390	4.442	1.360	379	4.251	1.576	492	4.084	1.407
Lab. Productivity (log)	42,273	4.456	1.274	40,017	4.455	1.271	1,385	4.651	1.160	379	4.422	1.197	492	3.969	1.689
Innovation objective (0-12)	42,323	4.083	5.100	40,062	3.739	4.975	1,390	10.160	2.931	379	9.575	3.866	492	10.644	2.428
Collaboration (0-10)	42,323	1.123	2.231	40,062	0.980	2.109	1,390	3.186	2.577	379	3.715	2.926	492	4.972	2.610
Degree (0/1)	37,802	0.549	0.498	35,541	0.527	0.499	1,390	0.919	0.273	379	0.802	0.399	492	0.953	0.211
Export (0/1)	42,323	0.286	0.452	40,062	0.263	0.440	1,390	0.718	0.450	379	0.480	0.500	492	0.795	0.404

2.5.2 Treatment variables

In order to measure the effect of tax support and grant support, three main treatment groups are defined: (1) Firms that received R&D tax incentive only, (2) Firms that received R&D grant only, and (3) Firms that received both tax incentive and grant.

In order to unravel how the above defined treatment participations impact firm private R&D, three (3) disjoint sets of experiments have been defined as detailed in Table 2.2.

Table 2.2: Public support participation

Treatment group	Control group	Description
Tax incentives only	No support	Dummy variable indicating 1 if firm received R&D tax incentive only, 0 if no support
Grant only	No support	Dummy variable indicating 1 if firm received R&D grant only, 0 if no support
Both tax incentives and grant	No support	Dummy variable indicating 1 if firm received both tax incentive and grant, 0 if no support

2.5.3 Covariates used in propensity score estimation

A separate propensity scores estimation was conducted for each of the three scenarios using logit regression with several covariates which may explain the probability of treatment participation. The choice of covariates for the matching is based on some exogenous factors that may influence participation in policy instrument as well as the target variable, in this case R&D investment (Caliendo and Kopeinig, 2008). That is, the chosen covariates in this study attempt to capture, or be correlated with, some of the factors that funding agencies may take into account when making selection decisions or firms' decision to participate in public support. For instance, the level of collaboration is likely to be correlated with the R&D intensity of the firms. The collaboration variable thus ranges from 0 to 12 indicating the extent of firms' external collaboration, which also accounts for the potential knowledge spillover effect that may result from the openness of individual firms' search strategies for external knowledge (Laursen and Salter, 2006; Battisti et al., 2015). Also included as a covariate is firm size, measured by the log of employment, to capture potential variations in the effects of public support across sub-groups of firms depending on size. Moreover, firm size can serve as a potential proxy for the likelihood of being financially constrained.

Also included as a covariate is the breadth of firms' innovation objectives which ranges from 0 to 12. Labour productivity (logged) is also included since it is likely to be correlated with the skills level of workers employed. A degree dummy to capture the capabilities of the workers employed, and another dummy variable indicating exporting behaviour to measure the international competitiveness of the firm. Included also as controls are regional dummies. The literature on the economic geography of innovation have highlighted the existence and importance of spatial dynamics in R&D activities. That is, contextual elements may mitigate or reinforce the spillover effect and create an indirect impact of policy instruments among treated firms as well as non-treated firms (Montmartin, Herrera and Massard, 2018). Spatial or geographic heterogeneity may also influence the reaction of focal firms to similar public interventions (i.e., firms in different territories may react differently to similar public instruments). Moreover, the impact of national R&D policies on R&D investment may vary depending on the economic structure of individual firms' geographical location (Montmartin, Herrera and Massard, 2018). Finally, included as controls are year dummies and industry (SIC 4-digit) dummies. Similar to regional dummies, the set of industry dummies may capture differences in funders' preferences in granting supports for products produced.

2.5.4 Outcome variables

The outcome variable considered is a binary indicator of internal R&D which reflects the extent of in-house R&D within the target population. Over the whole sample (Table 2.1), 21.5% of firms were R&D active. There are also notable overlaps between the outcome variable and the treatment variables: 90.6% of firms that received tax incentives only were R&D performers, 63.3% of firms that received grant only were R&D performers while 95.9% of firms that received both tax and grant supports were R&D performers. Meanwhile, 17% of firms that did not receive any public R&D support were R&D performers.

2.5.5 Propensity scores matching results

In order to account for the heterogenous likelihood of treatment participation for firms with different characteristics, we estimate a separate propensity score for each of the three participation scenarios listed in Table 2.2. In Table 2.3 we report the propensity score estimation results stemming from a linear logit model for the general sample. Briefly, the probability of participating in either grant or policy mix declines with firm size, while the probability of participating in any public support (i.e., participation in either tax only, grant only or both) declines with firm labour productivity. In particular, less productive, exporting firms with a broad scope of external collaboration, and innovation decision objectives are likely to participate in tax only support (column 2); low productivity firms with a broad scope of external collaboration, and broad innovation objectives are likely to participate in grant support only (column 4). Interestingly, in addition to being a small firm, all the factors that determine participation in tax incentives only also determine participation in policy mix (column 6). Meanwhile, firms' productivity, innovation objectives, and external collaboration prove to be critical determining factors in participation in any public funding.

2.5.6 Covariate balancing test after propensity score matching

Reported in Table 2.4 is the results of the balancing test confirming the reliability of the matched sample and the overall quality of our matching protocol for the full sample of firms. To confirm the balancing in the propensity score, we report variance ratios comparing continuous covariates between treated and control firms in the matched samples. We also report the after matching mean differences across the treated and control group for all the covariates used to estimate the propensity score. Where differences between treated and untreated firms were observed before matching, these are significantly reduced after matching. The bias after matching for all covariates is reduced below the 25% critical threshold, and the t-values for differences in the means are not significant. Most of the variance ratios are close to one

Table 2.3: Logit regression results for treatment participation - Full sample

	Tax only	Std. Err.	Grant only	Std. Err.	Both	Std. Err.
Employment	0.162	(0.1270)	-0.602**	(0.1910)	-0.474*	(0.2060)
Employment ²	-0.0139	(0.0132)	0.0599**	(0.0194)	0.0366	(0.0215)
Lab. productivity	-0.0580*	(0.0282)	-0.116*	(0.0502)	-0.388***	(0.0405)
Innovation objective	0.148***	(0.0096)	0.126***	(0.0170)	0.117***	(0.0199)
Collaboration	0.405***	(0.0380)	0.503***	(0.0730)	0.764***	(0.0725)
Collaboration ²	-0.0396***	(0.0045)	-0.0339***	(0.0081)	-0.0499***	(0.0074)
Degree (0/1)	0.041	(0.1130)	-0.652***	(0.1720)	-0.399	(0.2670)
Export (0/1)	0.708***	(0.0765)	-0.0113	(0.1430)	0.994***	(0.1460)
Intercept	-2.827***	(0.4870)	-0.011	(0.8910)	-1.354	(1.3300)
Sector: X²(p-value)	212.84	(0.0000)	60.8	(0.0000)	66.75	(0.0000)
Region: X²(p-value)	41.24	(0.0000)	35.92	(0.0000)	60.98	(0.0000)
Year: X²(p-value)	9.11	(0.0105)	17.85	(0.0001)	22.38	(0.0000)
Observations	17,380		11,146		8,654	
Pseudo-R^2	0.1719		0.1583		0.2763	
log likelihood	-3985.06		-1377.97		-1366.75	

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05.
χ^2 values indicate test on joint significance of sector, regional and year dummies.

Suggesting a consistent and balanced matching, and that there are no systematic differences in the observable covariates of treated and control firms before the participation in public support. Similarly, Figure 2.1 reports the graphs of the density distribution of the propensity scores estimated for the treated and control group before and after the matching procedure. We observe that, for all the three treatments, there are differences in the density distribution among the treated and control group before the matching, however, as required the common support condition appears to hold for all the treatments.

After the matching procedure, the graphs show that the propensity score matching significantly reduces the imbalance in the distribution. Moreover, the high degree of overlapping indicates the good quality of the matching procedure.

Table 2.4: Matching average balancing test

Tax only	Mean			Bias	t-test			Variance
	treated	control		Perc.	t-value	p-value		Ratio
Employment	4.438	4.458		1.4	0.37	0.711		0.99
Employment ²	21.550	21.732		1.4	0.37	0.715		1.02
Labour productivity	4.651	4.620		2.6	0.70	0.484		1.06
Innovation objective	10.160	10.322		3.7	1.39	0.165		0.86*
Collaboration	3.183	3.224		1.7	0.41	0.679		0.93
Collaboration ²	16.784	17.544		3.9	0.91	0.363		0.95
Degree	0.918	0.926		2.4	0.78	0.435		.
Export	0.718	0.694		5.2	1.42	0.155		.
Ps R²	LR-chi²	p>chi²	MeanBias	MedianBias	B	R	Treated	Untreated
0.002	8.88	0.353	2.80	2.50	11.40	0.90	1,377	1,377

Grant only	Mean			Bias	t-test			Variance
	treated	control		Perc.	t-value	p-value		Ratio
Employment	4.225	4.163		4.2	0.55	0.585		0.98
Employment ²	20.233	19.767		3.3	0.41	0.681		0.97
labour productivity	4.402	4.426		2.1	0.27	0.788		0.87
Innovation objective	9.556	9.321		5.0	0.79	0.428		0.87
Collaboration	3.700	3.469		8.8	1.09	0.276		1.05
Collaboration ²	22.251	20.197		9.7	1.13	0.257		1.08
Degree	0.809	0.793		3.9	0.55	0.582		.
Export	0.477	0.450		5.4	0.74	0.462		.
Ps R²	LR-chi²	p>chi²	MeanBias	MedianBias	B	R	Treated	Untreated
0.003	2.82	0.945	5.3	4.6	12.3	1.10	371	371

Both tax and grant	Mean			Bias	t-test			Variance
	treated	control		Perc.	t-value	p-value		Ratio
Employment	4.078	4.167		6.4	1.01	0.31		1.09
Employment ²	18.570	19.148		4.4	0.69	0.491		1.16
labour productivity	4.030	4.069		2.7	0.37	0.713		0.78*
Innovation objective	10.648	10.883		5.6	1.48	0.139		0.93
Collaboration	4.934	4.743		7.5	1.15	0.249		1.03
Collaboration ²	31.107	29.080		9.0	1.26	0.208		1.09
Degree	0.955	0.949		2.4	0.45	0.654		.
Export	0.798	0.819		4.7	0.81	0.415		.
Ps R²	LR-chi²	p>chi²	MeanBias	MedianBias	B	R	Treated	Untreated
0.006	8.35	0.400	5.3	5.1	18.6	1.09	486	486

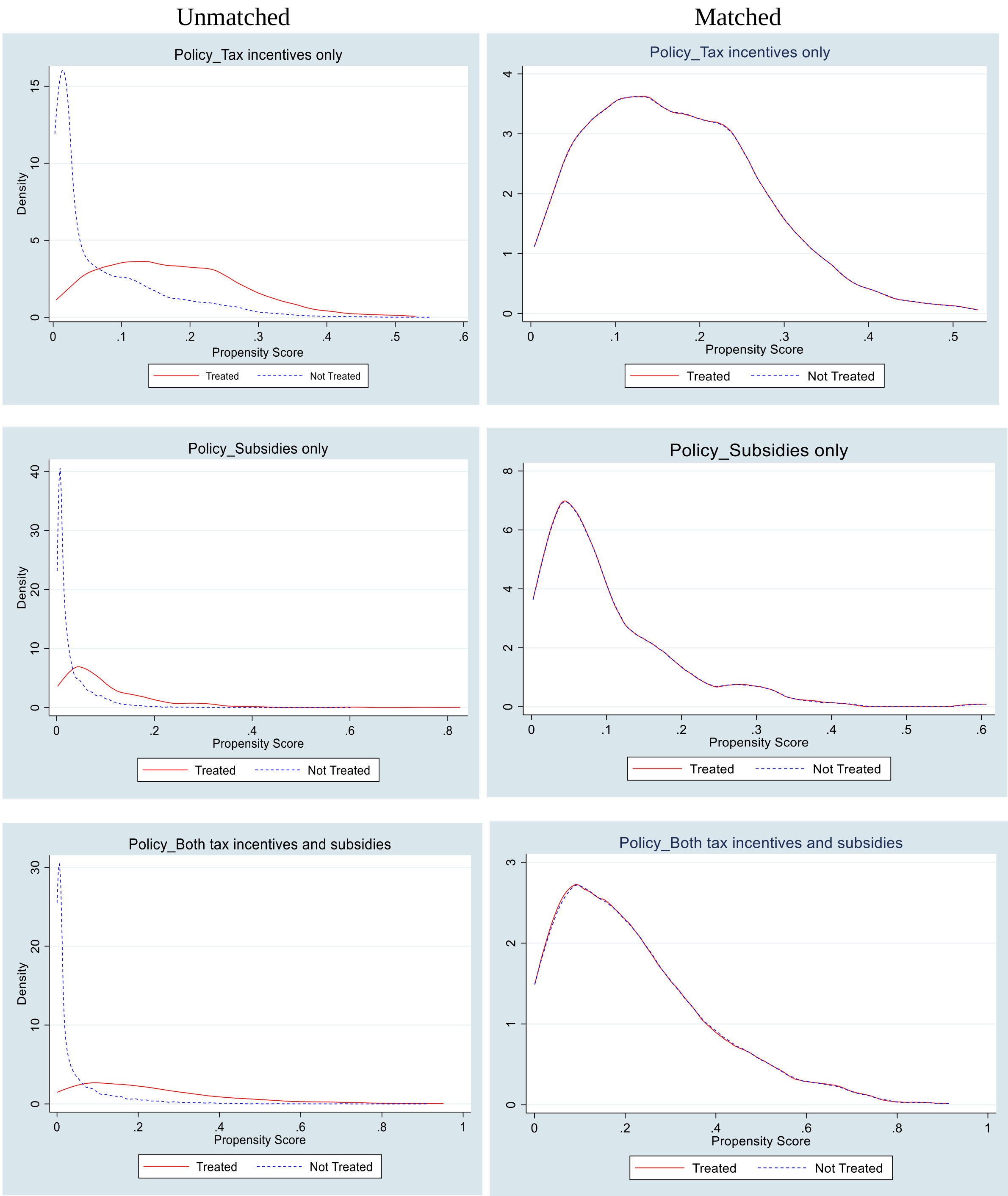

Fig 2.1. Distribution of the propensity scores of treated and non-treated groups before and after matching

2.6 Empirical Results and discussion

We examine the heterogenous impact of the UK's R&D support on the performance of different groups of participating firms. First, we estimate the general effect of tax-incentives-only, grants-only and a combination of both for the total sample of firms, providing several tests to substantiate the robustness of the results. Secondly, we explore the heterogenous impact across different characteristics based on a firm's size and productivity, technology intensity, knowledge intensity, and industrial distribution.

2.6.1 Policy impact on R&D - general effect

Since the covariate balancing test in Table 2.4 and the after matching propensity scores distributions in figure 2.1 appear to indicate a good matching performance, we can carefully interpret the average treatment effect on the treated (ATT), estimated through the multiple propensity score matching procedures, as the causal impact of the three different treatments on a firm's innovation input in terms of R&D investment.

Table 2.5 reports the results of the effect of public funding on R&D investment for the general sample as well as the robustness results. As pointed out in Section 2.5.2, four categories of firms are considered. The group of firms that receive no public support is the benchmark control group. The other three groups respectively consist of firms that receive tax-incentives-only, firms that receive grant-only support, and firms that receive both tax incentive and grant supports (i.e., policy mix). The reported ATT is the difference in averages between the matched treated and control groups. Since the outcome variable, internal R&D is dichotomous, the ATT's in the tables represent the difference in participation rate, and therefore represents the change in percentage points of the propensity to engage in R&D after participating in a particular treatment.

The results in Table 2.5 indicate that receiving either tax-incentives-only, grant-only, or a policy mix has a positive and significant impact on participating firms' internal R&D investment, thus, ruling out the crowding-out and confirming complementarity of public funding and firms' private R&D investment. Specifically, there are 31.4 percentage points more tax-incentive-only recipient firms that invested in R&D than firms that receive no public funding – confirming our hypothesis (2.H2), which states that *tax incentives in isolation will generate additionality effect on the R&D investment of participating firms in comparison to firms that receive no funding*. A comparison with the previous literature, which finds at the margin a dollar-for-dollar increase in R&D expense (Hall and Van Reenen, 2000), is difficult due to the dichotomous nature of treatment variable. However, our results point in the direction of the general results in the literature including Bloom et al. (2002) who found that tax incentives are effective in increasing R&D investment in nine OECD countries. Similarly, firms who receive grant-only support are 13.2 percentage points more likely to declare investment in R&D than firms that receive no public funding, also confirming hypothesis (2.H1) and coherent with the evidence provided by the large body of literature (Almus and Czarrnitzki, 2003; Czarrnitzki and Bento, 2014; Guerzoni and Raiteri, 2015) that reports a positive and significant effect of grant support on private R&D effort, ruling out the crowding out hypotheses and confirming the complementarity between public support and private investment in R&D. The results for 2.H1 and 2.H2 are also consistent with that of a recent meta-regression analysis of the tax incentives and grant literature, reporting significantly positive R&D investment effect from both supports (Dimos et al., 2022). The last group of treatment in our study (see column 4) concerns the possible interaction between R&D grants and R&D tax-incentives-only : The recorded ATT of 0.270 indicate that firms that receive policy mix are 27 percentage points more likely to declare investment in R&D than firms that receive no public support, also confirming our third hypothesis (2.H3) and again in line with the many studies that found a positive and significant effect of public policy mix on the private R&D expenses of participating firms when compared with firms that receive no public support (e.g., Guerzoni and Raiteri, 2015; Neicu et al., 2016; Marino et al., 2016; Pless 2021). However, comparing the strength of R&D input additionality across the three policy treatments we notice that the significantly positive policy mix effect of 27 percentage points is smaller when compared with the tax-incentives only effect of 31.4 percentage points, but larger when compared with the grant-only effect of 13.2 percentage points – this seems to suggest that the effectiveness of tax incentives is slightly attenuated when used in combination with grants, or munificent financial resource reducing the R&D investment benefit of public support (Wang and Zhou, 2022). Alternatively, grants could be enjoying a complementarity benefit from tax-incentives. That is, in terms of magnitude we do not find confirmation for hypothesis 2.H4 which states that receiving policy mix will generate a stronger input additionality effect than receiving either tax incentives or grant support in isolation. Although the result seems to contrast with studies such as the one for the 27 member states of the UE, Norway and Switzerland by Guerzoni and Reiteri (2015) which indicates that a mix of tax credits and grants produces significantly higher R&D input additionality than the additionality of the individual policies in isolation, it is on the other hand coherent with the study for France by Marino et al.

(2016) and that for Belgium by Dumont (2017), both studies suggesting that the effectiveness of public support decreases when different policy instruments interact. Suffice to say, the confidence interval for the tax only point estimate [0.2821, 0.3459] and that of the policy mix [0.2226, 0.3174] overlap indicating that there is no statistically robust difference between the two estimates. This means that we can confidently rule out the existence of contamination when tax support is mixed with grant support. Nevertheless, we will still caution readers that a comparison of magnitudes should be done with care since the treatments are binary variables.

Meanwhile, the result for the general sample is consistent and robust to additional tests where we used a kernel matching technique with very similar ATT's (see column 5 – column 7 of Table 2.5) and have consistent statistical significance when considering all the three treatment models.

Table 2.5: Impact of participation in public support on R&D performance – Full sample and robustness

	Full sample – PSM matching				Full sample – Kernel matching		
	Tax only	Grant only	Both		Tax only	Grant only	Both
Internal R&D	0.314***	0.132***	0.270***		0.378***	0.256***	0.338***
	(0.016)	(0.035)	(0.024)		(0.015)	(0.029)	(0.027)
No. Treated	1,377	371	486		1,377	372	490

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations.

Research has found that the impact of public support on firms' performance may vary depending on other firms' characteristics (e.g., see Vanino et al., 2019; Czarnitzki and Lopes-Bento, 2014; Dimos and Pugh, 2016). We therefore evaluate the impact of participation on the performance of firms across size distribution in Table 2.6, across sector-specific characteristics in Table 2.7, and productivity distribution in Table 2.8.

2.6.2 Policy impact across sizeband

Presented in Table 2.6 is our analysis of public support distributed across small firms and medium-large firms. We observe that each of the three policy treatments has a positive and significant impact on R&D investment regardless of firm size. Participation in policy mix has a similar effect on the R&D investment of both small and medium-large firms, about 24 percentage point more R&D investments among the treated relative to their untreated counterparts. Nonetheless, the effect both of tax-incentives-only and grant-only is consistently higher for small firms, respectively around 35% and 12% compared to the 28% and 9% in medium-large firms. This is an interesting finding owing to the fact that small firms often do not undertake R&D on a permanent basis compared to larger firms and well-established R&D intensive businesses (Kobayashi Yohei, 2014). Our result is evident, as found by Becker (2015) and Vanino et al. (2019), participating small firms generally experience the largest performance benefit relative to their untreated counterparts. Similar conclusion is made by Castellacci and Lie (2015) suggesting that on average, the additionality effect of tax credits is larger in small firms than in large firms. This is also a reflection that more small firms, on average, undertake R&D than larger firms. That said, we do expect to observe a greater R&D input effect of policy support among participating small firms: since resource constraints of small firms are greater than those of large firms, the likelihood of small firms using support effectively may be greater even if their innovative capability is not that strong. For instance, for small firms, there may be greater managerial attention on innovation: the management of a funded small firms may decide to hire high quality R&D personnel, incentivize their staff with higher salaries to work hard and/or offer innovation training for their staff, all aimed at producing a commercial innovation output, hence the greater the likelihood of using funding effectively. Our findings also coincide with the theory around bricolage, meaning that small firms which are often resource constrained tend to "make do" with existing or alternative resources to concoct the required potential to accomplish an innovation (Lvi-Strauss, 1966; Barker and Nelson, 2005).

Table 2.6: Impact of participation in public support on R&D performance across size

	Small firms (10 – 49 employment)			Medium – large firms (50+ employment)		
	Tax only	Grant only	Both	Tax only	Grant only	Both
Internal R&D	0.348***	0.123*	0.238***	0.279***	0.099*	0.245***
	(0.027)	(0.056)	(0.035)	(0.019)	(0.045)	(0.033)
No. Treated	469	162	239	906	202	241

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations

2.6.3 Policy impact across industry

Here we analyse the potential sector-specific patterns of the effectiveness of public support in spurring firms' innovativeness, differentiating between manufacturing and service firms[4], high-tech firms and low-tech firms, and between knowledge-intensive services (KIS) firms and less-knowledge-intensive services (LKIS) firms. In this analysis, high-tech firms consist of high technology manufacturing and medium-high technology manufacturing as per Eurostat's NACE 2-digit level classification. Low-tech firms on the other hand consist of medium-low technology manufacturing and low technology manufacturing as per the NACE 2-digit level classification. Service firms are also classified into KIS and LKIS based on the NACE 2-digit level[5]. The results are presented in Table 2.7.

Differentiating between manufacturing and service firms, grant-only seems to promote R&D investment only in service firms, with additionality of about 11 percentage points. This is surprising given that service firms rarely have an R&D department or labs (Sundbo, 1997): Unlike manufacturing firms which are typical R&D performers, service firms generally innovate through different variety of strategies of which R&D is not the dominant approach (Castellacci, 2008). Note also that the effect of both tax-incentives-only and policy mix on R&D is greater for service firms, respectively at 35.5 and 30.4 percentage points, compared to the 23.6 and 20.2 percentage points for manufacturing firms. These findings are similar to that of previous literature suggesting greater R&D input additionality effect of tax credits among participating service firms (Castellacci and Lie, 2015) and smaller R&D input effects of both tax credits and grants among samples of R&D performing firms (Dimos et al., 2022). Typically, there are more manufacturing industries that are R&D intensive and few service industries that are R&D intensive (Galindo-Rueda and Verger, 2016). Nonetheless, public support is given across all industries. While it may be in line to expect greater R&D additionality for the manufacturing industry, the typical diminishing return hypothesis appears to have set in due to the fact that more manufacturing than service industries undertake R&D, making any R&D additionality relative to their untreated counterparts more obvious for the service industries. Another reason for the additionality in the service sectors could be the quicker payback period

[4] Manufacturing sectors includes all industries with SIC2007 code:10-33. Services sector includes industries with SIC2007 code: >=45

[5] (High-tech manufacturing: 21 and 26) (Medium-high tech manufacturing: 20 and 27-30) (Medium-low-tech: 19, 22-25 and 33) (Low-tech manufacturing: 10-18, 31 and 32) (KIS: 50, 51, 58-66, 69-75, 78, 80 and 84-93) (LKIS: 45-47, 49, 52, 53, 55, 56, 68, 77, 79, 81-82, 94-96 and 97-99)

for R&D in service investments due to the smaller initial capital outlay for R&D in services than in manufacturing (Ehie and Olibe, 2010), Nonetheless, our results thus highlight the benefit of support for the service industries which may be regarded as “R&D-intensity constraint”.

Differentiating between high-tech and low-tech manufacturing, while the effect of grant-only on R&D in high-tech manufacturing is negative albeit insignificant, we now observe a significantly positive effect of grant-only among participating firms operating in the low-tech sector, firm experiencing as high as about 30 percentage points R&D additionality. While high-tech manufacturing are presumably intensive in terms of R&D investment, the result observed here indicates that for high-tech manufacturing in our sample, public grant support results in a deadweight loss; firms undertake the same level of R&D investment with and without grant support. This finding is generally consistent with the results of prior meta-regression analysis indicating lower effectiveness of grant for high-tech industries (Dimos and Pugh, 2016; Dimos et al., 2022). Note also that the effect of both tax-incentives-only and policy mix on R&D investment is greater for low-tech manufacturing firms, respectively at 26.4 and 36.4 percentage points, compared to only 19.5 and 11.3 percentage points for high-tech manufacturing firms. Our result so far appears to suggest that grant-only can support firms and industries that are new to R&D. It also highlights the benefits of public R&D support in general for firms that are otherwise not R&D intensive. Arguably, the low-tech firms in our sample are not the typical low-tech businesses, but self-select into a process of moving from being low on technology intensity to a higher state of intensity. Thus, continuous grant funding for instance would facilitate transitioning treated low-tech businesses into high-tech ones. In reference to previous literature, similar result was found by Gonzalez and Pazo (2008) which indicates that grants stimulate more private R&D spending in firms operating in low-technology sectors than firms in high-tech manufacturing industries. Castellacci and Lie’s (2015) meta-analysis also indicates that, on average, the additionality effect of a tax credit is larger in low-tech than in high-tech industries. A similar result is reported in the OECD, September 2020 publication indicating that firms in high R&D intensive industries are associated with little input additionality of R&D tax-incentives-only.

Finally, differentiating between KIS and less-KIS firms, participation in grant-only support promote R&D investment only in KIS firms, with participating KIS firms experiencing 13.4 percentage points R&D additionality. However, participating less-KIS firms benefit substantially more in terms of tax-incentives-only and policy mix effect compared with those in KIS, thus 47.9% versus 32.6% additionality from tax-incentives only, and 34.6% versus 28.8% additionality from policy mix. This latter result highlights the benefit of public R&D support for less-KIS in promoting valuable knowledge creation and innovation capacity building.

2.6.4 Policy impact across the productivity spectrum

Finally, the result of the analysis of the impact of participation in public support across the productivity distribution is reported in Table 2.8 and indicates a significantly positive effect of tax incentive only and policy mix on participating firms' R&D investment, irrespective of a firm's productivity level, although the effect of tax-incentive-only reduces in magnitude as one moves up the productivity ladder. Note that only the least productive firms (i.e., firms in the 1st quartile) record a significant positive effect of grant-only, about 21 percentage points more treated than untreated firms investing in R&D. Note also that the positive effect of all the three policy interventions is much larger for the least productive firms in our sample. This confirms, as suggested by Becker (2015) and found by Vanino et al. (2019), less productive participating firms experience the largest performance benefit relative to their untreated counterparts. Our result seems to highlight the fact that least productive firms have incentive to initially chose and invest more in "low hanging" technologies with low marginal cost and high marginal return (Blalock and Simon, 2009).

Table 2.7: Impact of participation in public support on R&D performance – Manufacturing and service

	Manufacturing			Manufacturing – HT			Manufacturing – LT		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Internal R&D	0.236***	0.096*	0.202***	0.195***	-0.0816	0.113*	0.264***	0.296***	0.364***
	(0.025)	(0.057)	(0.039)	(0.032)	(0.060)	(0.048)	(0.035)	(0.075)	(0.067)
No. Treated	504	104	173	261	49	115	242	54	55

	Service			KIS			Less-KIS		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Internal R&D	0.355***	0.112**	0.304***	0.326***	0.134**	0.288***	0.479***	0.0549	0.346***
	(0.020)	(0.043)	(0.036)	(0.024)	(0.053)	(0.037)	(0.044)	(0.068)	(0.112)
No. Treated	859	258	306	644	164	274	215	91	26

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations

Table 2.8: Impact of participation in public support on R&D performance across productivity distribution (quartiles)

	1st quartile			2nd quartile			3rd quartile			4th quartile		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Internal R&D	0.341***	0.207**	0.362***	0.320***	0.0778	0.151***	0.294***	0.086	0.242***	0.266***	0.136	0.155***
	(0.031)	(0.078)	(0.046)	(0.032)	(0.069)	(0.041)	(0.032)	(0.064)	(0.049)	(0.033)	(0.072)	(0.050)
No. Treated	343	87	116	344	90	119	344	93	120	342	88	116

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations

Table 2.9: Symbolic representation of R&D input additionality research results

	Tax only	Grant only	Both
Full results	+	+	$+^{<}$
Small	+	+	$+^{<}$
Medium-large	+	+	$+^{<}$
Manufacturing	+	(+)	$+^{<}$
High-tech manufacturing	+	(-)	$+^{<}$
Low-tech manufacturing	+	+	++
Services	+	+	$+^{<}$
KIS	+	+	$+^{<}$
LKIS	+	(+)	$+^{<}$
Productivity frontiers			
1st quartile	+	+	$+^{<}$
2nd quartile	+	(+)	$+^{<}$
3rd quartile	+	(+)	$+^{<}$
4th quartile	+	(+)	$+^{<}$

Notes:

\+ means significant positive effect

++ means significant positive effect of mix is larger than effect of both tax-only and grant-only

$+^{<}$ means significant positive effect of mix is smaller than effect of either tax-only or grant-only

(+) means insignificant positive effect

(-) means insignificant negative effect.

2.7 Conclusion

In this paper, we analyzed the R&D input additionality effect of public policy mix in the UK economy. While the individual impact of public R&D grants and tax incentives on business innovation input has received considerable attention in the literature, the analysis of the impact of a mix of R&D grant and tax incentives, particularly as it applies to the UK economy is still limited. The fundamental question in the public policy literature is whether public supports substitute for businesses' private investment efforts, complement them, or even favour their increase. Moreover, businesses often benefit from mixes of public support instruments which tend to interact and influence the effect of one another. The central argument in the literature has been the need to analyse the joint effect of support instruments in mixes to avoid under- or over-estimation of individual instrument effect – thus, the focus of this study.

Using coarsened exact with propensity score matching techniques and data sourced from three consecutive UK Innovation Surveys, we provide evidence of the effectiveness of receiving a mix of tax incentives and grants in spurring private investment in R&D. We also provide evidence of the effectiveness of the individual policy tools in stimulating firms' private investment in R&D. Table 2.9 provides a symbolic summary of all the results produced in Chapter 2 (see Table 2.5 to Table 2.8 for the actual estimated ATT's and their respective significance level). The results (based on final matched treated samples of 1,377 tax-incentives-only recipients, 371 grants-only recipients and 486 both tax and grant recipients) suggest that in comparison to firms that receive no public support tax incentives alone, grants alone or a mix of both significantly promote additional R&D investment in participating firms, thus suggesting complementarity of public funding and firms own investment in R&D and ruling out the substitution or crowding-out hypotheses. Nonetheless, there seems to exist a substitution effect when tax incentives and direct grants interact since the result indicates that the policy mix effect on R&D investment is smaller when compared with the effect of tax incentives alone and larger when compared with grants in isolation. That is, in terms of magnitude, our results seem to indicate that tax incentives are more effective than a policy mix in stimulating private R&D investment, whilst a policy mix is more effective than an R&D grant in stimulating private R&D investment. This seems to suggest that the effectiveness of a public support in the UK diminishes when tax incentives interact with direct grants, specifically when compared with the effectiveness of tax incentives.

The fact that the additionality effect of the policy mix is smaller than that of tax-incentives-only may first indicate the existence of a limit to the impact that can be accrued from policy mixes. For instance, there is the possibility that receiving grants and tax incentives brings in levels of subsidy such that after a certain level of support, firms begin to substitute private funding with public support. The government is one of several sources of funding for firms' innovation projects, and although the effect of public funding implicitly assumes that such funding will not replace any funding from other sources, the private funding that has been supporting a firm's R&D project tends to diminish when government increases its funding to that project (Diamond, 1999). The reverse may also be true in that when government withdraws or reduces its funding for a project, private money comes in to partially fill the gap. Secondly, the effective support level of tax incentives depends on firms' ex-post tax position. In view of that, a firm which received a direct grant but with lower profit may not get much positive and significant credit – funds that could otherwise be directed to other profitable projects. Although in the UK, SMEs have the option of a cash refund if there is no tax liability to offset tax benefit, this option is not available to large firms. Another explanation could be the fact that grants often mechanically reduce total tax credit support. In the UK and USA, grant-funded R&D does not qualify for tax credit, suggesting substitutability of the two subsidy types. However, the indirect benefits of grant support, which is the potential for the firm to secure other equity finance through signalling will make tax credits and grants complementary. Moreover, the equity finance part of the project may subsequently qualify for tax benefits.

In exploring the policy mix impacts across the various firm characteristics, we find that the policy mix effect on R&D investment is higher for service than for manufacturing firms; higher for low-tech manufacturing than for high-tech manufacturing; and higher for Less-KIS firms than for KIS firms.

From a policy point of view, the result appears to suggest that the best-performing government policy is tax incentives, followed by a mix of tax incentives and direct grants, and grants in isolation seems to be the least effective in stimulating private expenditure in R&D. The relatively higher performance of tax incentives is not surprising since the UK's indirect support for firm-level R&D dominates direct grant support. Secondly, firms respond differently to policy mix depending on their individual-specific characteristics. That is, under some circumstances, tax incentives may be more effective than grants or policy mix in stimulating private investment in innovation activities. And under other circumstances, a policy mix may be more effective than grants. For instance, while there is no significant difference in the policy mix effect on small compared to medium-large firms, tax incentives-only or grants-only is more effective for small firms than for medium-large firms.

This paper makes several contributions including documenting the individual policy effect of R&D grants and R&D tax incentives as well as the effect when both policy tools interact. This is an extension to the current literature which often concentrates on evaluating policy supports in isolation. Second, the study provides evidence of a complementarity relationship between R&D tax incentives and policy mix on the one hand, and firms' own private R&D investment on the other hand, thereby disputing the 'crowding out' hypothesis. Indeed, firms who receive either tax incentives or policy mix have a higher propensity of investing their own money into R&D. Third, the study also provides an insight into a possible substitutability or contamination of the additionality effect of tax incentives when they interact with R&D grants. Another contribution to the literature is the fact that this study offers insight into the differing effect of policy support depending on firms' specific characteristics including size, productivity and sector specific characteristics. In summary, this study contributes to three related but separate sets of literature that evaluate R&D tax incentives only, R&D subsidiesgrants-only and policy mix.

2.8 Limitations and future research

While this study offers insightful evidence of the effectiveness of public policy, it is not free from limitations and thus calls for further research. One crucial limitation is the fact that the dataset used for the analysis does not provide information on the amounts of firms' R&D investment or public support. The study thus has to resort to dichotomous measures of R&D investment. This also means that the analysis of how different levels or intensity of public support may impact firms' private R&D investment is not feasible in this current study. This remains a critical challenge since at the moment, it is unclear exactly how much public support is enough to achieve a desirable private R&D investment. Exploring administrative data on the amount of tax incentives and direct R&D supports that are available to firms may help with the analysis of when a government may be under- or over-subsidising.

Another limitation particular to this study is the use of a large-scale secondary dataset. The analysis of a large-scale database such as the UKIS presents several questions that cannot be investigated without more direct observational research methods. First, a much greater knowledge is needed about how firms make strategic decisions in terms of project investment selection. Most of the studies on public support are based on secondary/indirect data and infer relationships from data and existing theoretical models. It would be useful to develop a number of qualitative studies of how different firms make their project selection and policy participation decisions. In-depth case study research and observational research may allow for a worthwhile description of how firms may decide to (or not) substitute their own R&D investment with government funding.

Another limitation, and thence future research challenge is to understand how firms' participation in public interventions changes over time. The approach taken by this current study focused on public supports and their additionality effects in one period. However, with future innovation surveys, it may be possible to examine whether the support participation patterns of firms change over time and the resultant effect on their R&D investment. Indeed, it would also be interesting to explore weather changes in industry-level R&D performance are reflected by changes in the participation patterns of individual focal firms.

Finally, the policy treatment considered in this study used firms that did not receive any public support at all as a control group. This approach does not directly examine how a policy mix performs vis-à-vis tax incentives and grants in isolation. Future research could extend this research by using participation in tax-incentive-only and grant-only supports as two distinct control groups for participation in a mix of both supports.

Chapter 3

3 Estimating policy mix effects: Grants and tax credit complementarities for innovation outcomes

Abstract

This paper analyses the effectiveness of public R&D support in promoting innovation outputs of UK firms. The focus is on the indirect impact of public support on innovation outputs measured by new product and new process development. We distinguish between the individual effects of R&D tax incentives and R&D grants as well as a combination of both support schemes – 'policy mix'. The empirical evidence suggests tax incentives in isolation promote output additionality while grants in isolation generally do not provide significance evidence of promoting output additionality in treated firms, except on product innovation in less-knowledge-intensive service (LKIS) firms, and process innovation in low-tech firms. Meanwhile, in comparison with the individual policies effect, policy mix promotes higher output additionalities in treated firms, suggesting a complementarity or synergistic effect between the two instruments. The observed higher output additionalities of policy mix are consistent in our analysis across different firm characteristics such as size, industry, productivity distributions, and across technology and knowledge intensity distributions. These results have practical implications in respect of the mechanisms through which governments seek to impact private sector innovation.

3.1 Introduction

R&D grants and R&D tax incentives are forms of public innovation policies employed by most governments to facilitate private sector innovation (Lenihan et al., 2020). Analysis of the individual effect of R&D grants and R&D tax incentives on business innovation output (e.g., patenting, product, and process innovation) has received some attention in the literature, although not as extensive as the consideration given to the evaluation of the individual impacts of the two policy tools on innovation inputs (e.g., R&D investment, R&D employment) (García-Quevedo, 2004). Very much more limited is the number of research studies which analyse the link between a policy mix and innovation output. This is in spite of the fact that businesses often benefit from mixes of diverse policy supports whose interactions may results in either a synergistic, neutral or even a substitute effect on performance (Cunningham et al., 2013; Lenihan and Mulligan, 2018; Vanino et al, 2019). Also, innovation is commonly listed as an essential for the attainment of a higher level of competitive performance. Consequently, the elements that impact firms' innovation performance are important areas for investigation. Particularly scarce are empirical studies which consider policy mix effects on innovation output as it pertains to the UK economy. To the best of our knowledge, there is no empirical study on the effectiveness of the UK's innovation policy mix in promoting output additionality among beneficiary firms.

Lenihan and Mulligan (2018) review the empirical literature on policy mix effects and note the particularly limited number of empirical studies on the policy mix as it applies to business innovation outputs. According to these authors, few empirical studies operationalise policy mix effects, particularly on innovation outputs primarily due to the lack of firm-level datasets which capture the variety of innovation measures beyond R&D expenditure as well as detailed information on the types of innovation supports businesses received. These authors, in consensus with many other scholars including Guerzoni and Raiteri (2015) and Rogge and Reichardt (2016), recommend that accessing datasets with comprehensive information on the policy mix which businesses receive may present the greatest analytical advantage for empirical studies. Nonetheless, it has been established in the literature that firms generally benefit from multiple instruments which leads to instrument interactions. The resultant effect of such interactions could be either synergistic (Haegeland and Møen, 2007; Guerzoni and Raiteri, 2015), neutral, or lead to a reduction in the potential effect of the individual policies (Marino et al., 2016). For instance, while Haegeland and Møen's (2007) study of Norwegian firms recorded a complementary effect when R&D grants interacted with the R&D tax credit, Marino et al. (2016) found evidence to suggest that mixing French tax credit with R&D grants reduces the additionality of public support. These findings among others have led to calls to use comprehensive datasets which enable instrument mix evaluations, since evaluating individual policies in isolation without accounting for other available supports may lead to a hidden treatment bias. That is, evaluating individual policies in isolation might lead to over- or under-estimation of the individual policy impact (Guerzoni and Raiteri, 2015; Busom et al., 2015)

The primary concern for public authorities on decisions regarding the level of their engagement with innovation support programs is whether public spending is complementary and thus crowds-in or additional to private sector innovation spending, or whether it substitutes for and thus crowds-out private sector spending. If a beneficiary firm uses public funds to undertake a project it would undertake in the absence of the support, then public support is said to substitute or crowd-out private funding. If on the other hand, public funding enables firms to undertake projects that they would otherwise not undertake in the absence of the support, or if the public support induces the firms to increase their innovation investments, then public support is said to complement or crowd-in private investment (i.e., in our case, if public support leads to an improvement in the innovation performance of treated firms). These arguments regarding the substitutability, additionality or complementarity as pertaining to public support and businesses' private innovation efforts have long been debated in the empirical literature. Although the overall finding by the literature is ambiguous, the majority of studies conclude on complementary between public and private funding (see e.g., Sterlacchini and Venturini, 2019; Czarnitzki and Hussinger, 2018). Meanwhile, studies including Almus and Czarnitzki (2003), and Kaiser (2004) found public funding either partially or fully crowds out private innovation investment. In fact, a review of the policy evaluation literature by Zúñiga-Vicente et al. (2014) found that 48 studies across various levels of aggregation concluded complementarity between public support and private innovation investment, 15 studies reported substitution effects and 14 studies reported insignificant results.

A major concern in the analysis of the differential performance effects between publicly supported and non-supported firms is the issue of selectivity and endogeneity. If the receipt of public support is related to some covariates (X) that are correlated with innovation performance but are not accounted for in our analysis, then any potential effect estimated in our evaluation may not necessarily reflect the true causal relationship between public support and innovation performance. In order to address this problem, we use the propensity score matching technique, commonly used in treatment evaluation literature (e.g., Heckman et al., 1997; Guerzoni and Raiteri, 2015; Vanino et al., 2019), to identify a valid counterfactual for the support receiving (i.e., treated) firms. The propensity score matching process allows us to control for any confounding influence of pre-treatment control variables in our dataset in order to estimate causal treatment effects.

Information used in conducting our analysis is sourced from the UK Innovation Survey dataset. The dataset provides information on public innovation supports relating to direct R&D grants and indirect R&D tax incentives. There is also information on various firm innovation indicators including product and process innovations, and on various firm specific characteristics.

The objective of this present study is to establish whether, first, the UK's R&D policy mix impacted on the performance of beneficiary firms in terms of their innovation outputs. Second, the study aimed to establish whether the interaction between policy instruments in a mix created either a synergistic-, neutral- or substitution-effect on beneficiary firms' innovation performance in comparison to the effect of individual policies. This is an important topic, firstly due to the empirical gaps already outlined at the beginning of this section. Second, the UK like other industrialised governments designs R&D tax incentives and R&D grants to induce increase in private sector innovation investments, and policy makers want to know if the goals of these policy initiatives are being achieved. Arguably, the UK is a particularly interesting case study as both R&D tax incentives and R&D grants have been used to improve the performance of firms (Vanino et al., 2019; Pless, 2020). Moreover, the UK over the 2012 to 2018 period has increased its support for business innovation activities from 0.16 % in 2012 to 0.33% of GDP in 2018 ranking the UK third among OECD countries (i.e., behind France and Russia) in providing the largest level of government support to business innovation investment as a percentage of GDP (OECD March, 2021). Another reason to particularly examine the impact of policies on innovation outputs is that firm-level innovations crucially shape the competitive performance landscape of any economy (Lengnick-Hall, 1992).

Firstly, the present study contributes to the limited literature on evaluating the effectiveness of the public R&D policy mix in promoting innovation output additionalities focusing on the experience of the United Kingdom. Secondly, we also provide analytical insight on the effectiveness of R&D tax incentives and R&D grants in isolation. By examining the effectiveness of the policy mix simultaneously with that of the individual policies, we extend previous studies which consider single policies in isolation. Thirdly, we provide insight on two output additionalities in terms of product and process innovation for tax-incentives-only, grants-only, and the policy mix – contributing to the limited literature on the output additionality of public support (e.g., Cerulli and Poti, 2012; Castellacci and Lie, 2015). A novel aspect of our contribution is the fact that we provide insight into the effects of supports based on firm specific characteristics. Previous studies have rarely considered simultaneously how contextual factors such as size, industry, knowledge and technology intensity levels, and firm productivity may define differentials in public support impacts. Although few studies have examined the impact of individual policies or a policy mix for specific types of firms including size (e.g., Pless 2021) and, manufacturing and service (e.g., Minniti and Venturini, 2017; Colombo et al., 2011), there is no study, to the best of our knowledge, that has provided a comprehensive analysis of the implications of policy supports for different industries, knowledge and technology intensities, and firm sizes and productivity levels. Our study therefore extends the current literature by providing a comprehensive evaluation of the impact of tax-incentives-only, grants only and the policy mix across product and process innovations over industries, firm sizes, firm knowledge and technology intensity level, and firm productivity level.

The remainder of Chapter 3 is structured as follows. Section 3.2 presents the conceptual framework of this paper, describing the mechanisms that link public innovation supports to firm-level innovation. Section 3.3 presents the related existing literature and the hypothesis development. The econometric estimation strategy is described in Section 3.4. Section 3.5 presents the data and the main descriptive statistics. This section also provides details on both the propensity scores estimations and the matched samples and balancing test results. Section 3.6 presents the main findings for additionalities in firms' innovation prospects in terms of product and process innovations. Section 3.7 presents conclusions, discusses some major findings and also derives the implications for policy makers. Finally, limitations and avenues for future research are presented in Section 3.8.

3.2 Conceptual framework

3.2.1 Public innovation support

Economists acknowledge technological development as the main factor for sustainable growth in highly industrialized economies. The private sector on the other hand is acknowledged as playing a critical role in ensuring a continuous advancement in technological development through the creation of valuable knowledge. Firms search for, create and accumulate knowledge through innovative activities – stocks of knowledge that would potentially be translated into successful innovation outcomes (Roper and Hewitt-Dundas, 2015). However, firms normally do not invest the optimal socially desirable amount of money in R&D and innovation activities due to the so-called market failures argument.

Due to the non-rival and non-exclusive nature of knowledge, part of the knowledge that is generated from businesses' private R&D and innovation activities spills over to other agents.

This social benefit to knowledge makes it difficult for an investing firm to fully appropriate the returns of its private investment (Arrow, 1962), even though it solely bears all the cost. Secondly, it is commonly known that R&D and innovative activities are inherently uncertain in that development projects may fail to attain the desired technological change or innovation outcome (Åstebro and Michela, 2005; Czarnitzki and Lopes-Bento, 2013; Vanino et al., 2019). Even in situations where projects are successful in terms of desired outcomes due to the effective application of the business' innovation input strategies, market related risks preclude a guaranteed successful commercialization of such innovations. Thus, successful project inputs can never perfectly predict successful outcome or innovation commercialization (Arrow, 1962). Moreover, due to the inherent high risk and uncertainties associated with R&D and innovation projects, businesses may find it difficult to obtain external finance or investors for their projects. Risk-averse firms unwilling to bear the high risk and uncertainty may sub-optimally allocate risk by discriminating against risky projects (Czarnitzki and Lopes-Bento, 2013) with potential high economic returns. All these factors interact in different ways that lead to a market failure such that the market, if left on its own, would not provide adequate incentives to firms' private investment in innovation.

Governments in industrialized economies correct market failure and facilitate firm private innovation by designing policy instruments or a combination of instruments which aim to reduce the cost of R&D and innovation projects (Radas et al., 2015) and hopefully induce greater additional private innovation effort on the part of firms. The concept of additionality is based on the notion that government intervention for R&D and innovation induces firms to undertake additional R&D and innovation investments that the firms would not have otherwise undertaken in the absence of the public intervention. If public intervention leads to additional private innovation efforts on the part of firms, then public innovation spending is said to be complementary to private innovation spending and thus, "crowd in" private innovation effort. On the other hand, if firms use public support to undertake projects that they would have done anyway without the public support, then public spending is said to substitute for and thus, "crowd out" private innovation spending.

Firms often receive combination of multiple supports (i.e., the policy mix) which leads to instrument interaction. For the purpose of our current study, we define "policy mix" as the combination of policy instruments which interact to influence the quantity and quality of innovation investments in the private sectors. Central to the policy mix concept is the composition of instruments in the mix and how they might interact to mutually enhance the effectiveness of each other (Cunningham et al., 2013), which implies that the impact of individual instruments is influenced by the direct or indirect effect of the other instruments in the mix (Rogge and Reichardt, 2016). The interdependencies of instruments effect essentially impacts the overall effect of the instrument mix (Flanagan et al., 2011). This over-all mix effect may be complementary (i.e., if policy mix produces a synergy effect to the individual instrument effect, or the presence of one instrument in the mix increases the effectiveness of another), or trade-offs (i.e., if the effectiveness of one instrument is weakened by another). There is also the possibility that one instrument has no effect on others in the mix or, the instruments complementarity or otherwise is essentially context specific. Meanwhile, for the policy maker, there is the question of whether instrument mix can achieve synergies and positive complementarities, and how any negative interaction between instruments can be reduced (Cunningham et al., 2013). The interest in possible complementarities, trade-offs or tensions between instruments in a mix is nothing new to policy makers and analysts alike, as both the theoretical and empirical literature tries to unravel the mechanisms of interdependence between policies in a mix. These interests and the fundamental aspects of the policy mix concept led us to a discussion of the mechanisms through which public support may impact the efficiency with which firms engage with the various stages of their innovation development process.

3.2.2 Effects of innovation support

The introduction of new products or processes represents the end of a process of knowledge sourcing and transformation by a firm (Roper et al., 2008). Public support may drive innovation output additionality by enhancing the scope and efficiency of the knowledge sourcing and transformation processes. Public policies have been found to have a significantly positive influence on firms' innovation processes in terms of their knowledge sourcing and transformation (see. E.g., Autio at al., 2008; Scandura, 2016). Following Grant and Baden-Fuller (2004), we identify the mechanisms through which public intervention can enhance the efficiency with which firms engage with the different aspects of the innovation process. By way of distinguishing, efficient knowledge search and acquisition implies creating, accumulating and replicating knowledge at a lower cost, while efficient knowledge transformation entails the ability to integrate multiple knowledge and to utilise knowledge to its full capacity.

3.2.3 Knowledge sourcing

We now explain how public supports may impact firms' innovation output by influencing the efficiency and scale of their knowledge sourcing processes. The implication of this is the ability of public support to facilitate an efficient and adequate level of knowledge exploration (March, 1991) and knowledge generation (Spender, 1992) that eventually increases the firms' stock of knowledge. Firms search and acquire valuable knowledge through their own research in the form of in-house R&D (Roper and Hewitt-Dundas, 2015; Love and Roper, 2001), buying the knowledge from an external research institution, or within the framework of external collaboration by forming strategic alliances (Laursen and Salter, 2006). These knowledge sourcing routes have differing implications on not only the scale of firms' knowledge search, but also the qualitative aspect of knowledge search in terms of the nature or kind of knowledge that the firms can realise. Similarly, public innovation support is a determining factor of the sourcing trajectory that firms engage with. Many studies have identified R&D, both in-house and outsource, as means of learning, creating and storing up valuable knowledge for innovation. Similarly, firms' external alliances enable access to partners' stocks of knowledge in order to exploit complementarity while still maintaining firms' distinctive base of specialized knowledge (Grant and Baden-Fuller, 2004).

Since public support reduces the private cost of innovation to firms, it allows firms to increase their knowledge creation efforts more than without the public support. Since the cost of replicating knowledge tend to be lower than the cost of the original knowledge creation, this implies firms can benefit from the economies of scale that characterise knowledge. Moreover, if the knowledge created through one innovation project is not specific to the production of a single product, then economies of scale also imply economies of scope: Firms can gain efficiency in their knowledge search and acquisition activities by replicating at a lower cost the knowledge created through funded projects in the execution of other profitable projects. There is also the direct effect of increasing the level of firm knowledge search and acquisition engagements.

Moreover, since public support de-risks innovation and provides liquidity for firms, it offers firms the opportunity to seek out different kind of knowledge including those related to riskier innovation. That is, the nature of knowledge that a firm seeks and the corresponding search strategy depend on the type of innovation the firm intends to undertake (Miotti and Sachwald, 2003). For instance, accessing knowledge from knowledge institutions such as universities has been found to be critical for radical or new to the market innovation. Public support such as innovation vouchers allows firms to access cutting-edge and specialist knowledge from external knowledge institution for such innovations. Research indicates that, publicly funded firms tend to collaborate with external knowledge institutions. Public support may encourage and facilitate collaborations between firms and publicly funded research institutions (Intarakumnerd and Goto, 2018) within the national innovation system, which can subsequently influence the nature of knowledge search and acquisition, for instance, undertaking more basic and applied research in comparison with experimental R&D (Mulligan et al., 2022). Alliances with the knowledge institution also enable firms to access unique and highly specific knowledge through slipovers and facilitate the building up of the firms' in-house R&D capability for subsequent innovation projects.

3.2.4 Knowledge transformation

In this section we focus on how public funding influences the efficiency with which knowledge assets are transformed into innovation outputs. Consistent with the argument of Grant and Baden-Fuller (2004), if the production of innovation outputs entails the combination of different kinds of specialized knowledge, each of which is subject to economies of scale and scope, then efficient knowledge transformation implies: one, firms are able to integrate the different kinds of specialized knowledge to produce innovation outputs at a lower cost through applications of higher order organizing principles (Kogut and Zander, 1992). Two, firms are able to utilise knowledge to its full capacity. Since knowledge is subject to economies of scope, but also, not specific to a single product, this may mean that any extra capacity in knowledge generated through funded projects can be used by firms to expand the scope of their innovation. For instance, government support in terms of taxation-related financial slack has been found to impact the internal management capabilities of firms in terms of their risk management and accelerating R&D projects (Teirlinck and Spithoven, 2012).

3.3 Hypotheses development

3.3.1 Fiscal policies and innovation output

Although evaluations of the output additionality of tax incentives have been noted as limited in the literature, several studies have evaluated the output additionality effect of R&D tax incentives. Using matching techniques, Freitas et al. (2017) firm-level analysis of the additionality effect of R&D tax credits across three countries (i.e., Norway, Italy and France) suggested that firms in industries with high R&D orientation exhibited stronger output additionality on average in terms of turnover from new products. Output additionality effects across the three countries were however different. Using matching methods, Bozio et al. (2014) document that, in France, the 2008 R&D tax reform which transitioned the tax system into a more generous one led to a large increase in the number of firms claiming the public support. Evaluation of the effectiveness of the reform indicates a significant increase in the R&D spending of firms that claimed the public support compared with firms that did not make a claim. Nonetheless, there was no evidence of firm-level output additionality in terms of the number of patents up to 2 years after the implementation of the reform. Using a non-parametric approach, Czarnitzki et al. (2011) evaluated the effect of R&D tax credits on various innovation outputs of Canadian manufacturing firms. Firms that received tax credits exhibit significantly better scores on most innovation performance indicators, thus, tax credits increased the probability that a firm introduced new-to-the world and new-to the market products, the number of newly introduced products, and share of sales with new products. Cappelen et al. (2012), found that the Norwegian R&D tax incentive, introduced in 2002, led to the development of new production processes and new products in participating firms. The authors found no evidence of R&D tax impact on innovation output in terms of patenting and new-to-the-market products. In contrast to Cappelen and colleagues, Aralica and Botric's (2013) study of the effectiveness of R&D tax incentives in Croatia found positive and significant impact on innovation output in terms of product innovation**.** Similarly, Westmore (2013) examined the output additionality effects of R&D tax incentives across 19 OECD countries and found positive effects on patenting**.** Ernst and Spengel (2011) study on European corporations between the period of 1998-2007 found positive effect of R&D tax credit on patenting.

It is often argued that, even if public R&D grants induced additional innovation input efforts such as investment in R&D, the induced effect may not necessarily lead to an output additionality. In view of this, few studies have considered both input and output additionalities of public R&D grants. Czarnitzki and Hussinger (2018) use a matching technique to analyse the effects of public R&D funding on R&D spending and the subsequent effect on the patenting behaviour of German firms. The authors found that public R&D grants not only induce additional R&D spending in subsidised firms (37% more than in non-subsidized firms), but also accelerate their R&D spending (27% more than in non-subsidized firms). Thereafter, the induced additional R&D spending subsequently led to 6.6% increase in patenting and 9.0% increase in patent quality. Beck et al.'s (2016) study of the effectiveness of Swiss public R&D grant designed to incentivise radical and incremental innovations found induced R&D spending in respect of the policy support had a significant effect on the radical innovations of participating firms. In the same spirit, Czarnitzki and Delanote (2015) evaluated the input and output additionality of national and EU R&D grants for young SMEs in Germany. They find R&D grants induce additional R&D spending and R&D employment in both high-tech and low-tech SMEs, with the additionality effect being highest in high-tech SMEs. Their result also indicates that the induced R&D input subsequently led to a higher output additionality in terms of patenting.

As mentioned in the earlier sections, empirical evidence about the output additionality effect of the policy mix is limited (Bérubé and Mohnen, 2009 and Radas et al., 2015). Bérubé and Mohnen (2009) study of Canadian manufacturing businesses is one of the few studies that consider innovation output additionalities of the policy mix. Using a sample of 2,785 and non-parametric matching technique, the authors examine the effectiveness of Canada's public R&D grants by comparing the innovation performance of businesses that receive tax credits only with that of businesses that receive a mix of tax credits and grants. Their findings suggest that businesses that benefit from both policy instruments introduced more new products than businesses that benefit from only R&D tax credits. Receiving a policy mix also leads to more first-world innovations and more successful innovation commercialization than receiving only tax credits. In the same spirit, Radas et al.'s (2015) paper on the Croatian SMEs also find that mixing tax incentives and grants strengthened treated firms' output additionality in term of number of innovations and sales from innovations. Becker et al. (2017) use panel data on UK and Spain to examine the effectiveness of regional, national and EU innovation supports on businesses innovation activities and innovation commercialization successes. Their results indicate that for both the UK and Spain, national support is correlated both with a greater probability of product/service innovation, and also the degree of novelty of product/service innovations. We therefore propose the following hypotheses in respect of output additionalities:

(1) Additionalities in product innovation

3.H1a: *Tax incentive in isolation will generate additionality effect on product innovation of participating firms in comparison to firms that receive no funding.*

3.H1b: *Direct grant in isolation will generate additionality effect on product innovation of participating firms in comparison to firms that receive no funding.*

3.H1c: *A mix of tax incentive and direct grant will generate a stronger additionality effect on product innovation than the additionality effects in 3.H1a and 3.H1b.*

(2) Additionalities in process innovation

3.H2a: *Tax incentive in isolation will generate additionality effect on process innovation of participating firms in comparison to firms that receive no funding.*

3.H2b: *Direct grant in isolation will generate additionality effect on process innovation of participating firms in comparison to firms that receive no funding.*

3.H2c: *A mix of tax incentive and direct grant will generate a stronger additionality effect on process innovation than the additionality effects in 3.H2a and 3.H2b.*

3.4 Econometric method

In observational data there are the problems of possible endogeneity and selection biases associated with the allocation decisions of funding agencies and firms self-selecting into support programmes. This means that directly comparing the outcomes of treatment and non-treated firms may be misleading since there may be systematic differences between the two groups. Rubin (1977) introduced the conditional independence assumption (CIA) to address this problem. According to the CIA, potential outcomes are independent of treatment assignment given a set of observable covariates X which are not affected by the treatment. The CIA allows us to employ matching methods to pair treated with non-treated observations which are as similar as possible on the observable covariates X and use the latter group to estimate the counterfactual scenario. The advantage of matching methods is that they require no assumptions about functional forms and the distributions of the error term. The downside, however, is that they only control for the selection on observables. We therefore maintain the assumption that all the important factors driving selection into treatment are observed. Meanwhile, due to the 'curse of dimensionality', a balance score such as propensity score can be defined so that a direct comparison between treated group and non-treated group may be more meaningful (Rosenbaum and Rubin, 1983).

We test whether public supports complement or crowd-out private innovation efforts by conducting a treatment analysis. We estimate on average, the likelihood of subsidised firms innovating if they had not been funded. This can be illustrated by an equation describing the Average effect of Treatment on the Treated firms (ATT)

$$ATT = E(Y^T \,|S = 1) - E(Y^C|S = 1) \quad (7)$$

Where Y^T is the outcome variable (product innovation and process innovation), $(S = 1)$ refers to the treatment group and so $(S = 0)$ refers to the control group. Y^C is the potential outcome which would have been realised if the treatment group $(S = 1)$ had not been treated. An ATT>0 will indicate a complementarity between public support and private innovation efforts.

The CIA assumption would imply

$$E(Y^C \,|S = 1, X) = E(Y^C \mid S = 0, X) \quad (8)$$

And the average effect of treatment on the treated can be estimated as

$$ATT = E(Y^T \mid S = 1, X = x) - E(Y^C \mid S = 0, X = x) \quad (9)$$

We first estimated the probability that any firm participates in a particular public funding based on a set of relevant observable characteristics which have been found to influence the likelihood of public fund participation in the previous literature. We use a logit model to estimate the propensity score for all observations, using several covariates which may explain the probability of participation. We then conducted a Nearest-Neighbour matching technique with a strict Caliper bandwidth, where each treated firm is paired with the single closest non-treated firm within a 0.05 range in the propensity score. The pairs are chosen based on the similarity in the estimated probability (i.e., propensity score) of participation in a particular public support. Matching is done with replacement, so each observation in the control group can be used as a match multiple times.

To ensure that the overlap assumption is satisfied, the samples of treated and control are restricted to a common support by calculating the minimum and the maximum of the propensity scores of the potential control group and deleting observations on the treated firms with probabilities smaller than the minimum and larger than the maximum in the potential control group. We also ensured that the propensity scores are "balanced" in terms of having a similar distribution in the treated and control group. Balance in individual covariates across treatment and control groups (Austin, 2009) were also ensured before we finally conducted the ATT estimation. Standard errors were clustered following Abadie and Imbens (2016) methodology for the nearest-neighbour matching procedure to account for the additional source of variability introduced by the estimation of the propensity score (Heckman et al., 1997).

Finally, to test the sensitivity of the matching method, as a robustness check we temporarily coarsened the employment, collaboration, degree, export, year of survey, and sector variables for the purpose of matching. Next, we sorted observations into strata, each of which has the same values of the coarsened variables. We then pruned from our dataset the observations in any stratum that did not include at least one treated and one control observation. We finally matched the remaining treated and control observations using the propensity score before estimating the causal effect of treatment. The use of coarsened exact matching strata with propensity score matching improves the balance of matched samples and the quality of the inferences drawn from propensity score matching (Blackwell et al., 2009; Iacus et al., 2012).

3.5 Empirical analysis

3.5.1 The data

For the empirical part of this study, we pooled three cross-sectional surveys from the UK innovation UK Innovation Survey (UKIS) which had individually been merged with the Business Structure Database (BSD) by the UK Data Service. These comprise UKIS 2015 covering the 2012-2014 period, UKIS 2017 covering 2014-2016 period and UKIS 2019 covering the 2016-2018 period. Each survey covers the innovation activities of firms with 10 or more employees, in all industries and across all UK regions.

Table 3.1 presents the correlation matrix of the variables used in our analysis. We find that the employment and productivity variables are not highly correlated with product innovation and process innovation variables. The firms' external collaboration and innovation objective on the other hand are positively and highly correlated with product innovation and process innovation. The highest correlations observed are those of the innovation objective variable with product innovation (0.552) and with process innovation (0.444). The extent of firms' collaboration is next at (0.409; 0.331) respectively with product innovation and process innovation. Similar correlation patterns are observed for the tax only, grant only and both supports variables. For instance, we observe the highest correlations between the innovation objective and tax only (0.229), grant only (0.113), and both supports (0.151). The correlations of firm's collaboration are next highest at (0.184; 0.124; 0.202) respectively with tax only, grant only and both supports. However, in contrast to their correlation with (product innovation and process innovation), firms' employment and productivity are positively corrected with tax only (at 0.033 and 0.028) and negatively correlated with both supports (at -0.007 and -0.042). In respect of participation in grant only, we find a positive correlation with employment (0.005) and a negative correlation with productivity (-0.003).

3.5.2 Outcome Variables

Researchers have operationalised innovation success by several indicators Including patenting, the proportion of total sales derived from products newly developed, new processes and products. Innovation in the UKIS is represented by three main indicators: any new or improved products introduced during the previous 3 years, any new improved process introduced during the previous 3 years, and the proportion of total sales (at the end of each 3-year period) derived from newly introduced products during the previous 3 years.

Following Roper et al. (2008) and based on the recommendation of Pittaway et al. (2004) who emphasised the importance of analysing product and process innovations together. We anticipate that different policy interventions may have differential product and process effects. Our first innovation outcome variable is therefore measured by a binary indicator of product innovation which reflects the extent of product innovation within the target population. Our second innovation outcome variable is similarly measured by a binary indicator of process innovation which reflects the extent of process innovation within the target population. Product (process) innovation is defined as the new or significantly improved product (process) introduced by the firm during the previous 3 years of the UKIS survey period. Over the full sample (see Table 3.2), 23% of firms were product innovators whiles 16.8% of firms were process innovators. There are also notable overlaps between the two innovation outcomes and the treatment variables: 69.1% (47.3%) of firms that received tax-only were product (process) innovators, 50.2% (39.6%) of firms that received grant-only were product (process) innovators, while 71.2% (55.7%) of firms that received both tax and grant supports were product (process) innovators. Meanwhile 20.5% (15.0%) of firms that received no public support were product(process) innovators.

3.5.3 Treatment variables

Our dataset allows us the opportunity to operationalise all the policy treatments described in the conceptual section. We exploit information on two public supports at our disposal in the dataset to design three different treatments and one control group for all the treatment groups. There are two survey questions in the UKIS asking whether firm received financial support from the UK central government during the 3-year period. The first question relates to the receipt of direct support in the form of Smart or Collaborative R&D grants, working with Catapult centres or Innovation vouchers and the second question relates to the receipt of indirect support such as R&D tax credits and patent box. The three policy treatments which were created from the two survey questions include: firms benefiting from tax incentives only, firms receiving grants only, and firms receiving a mix of tax incentives and grants. The control group for all the three treatments consist of firms that did not benefit from any public support. Of the full sample, 40,062 firms received no public support representing (94.66%), 1,390 (3.28%) received tax incentives only, 379 (0.90%) received grants only and 492 (1.16%) received both tax incentives and grants supports (see Table 3.2). 69.1% of firms that received tax incentives only were product innovators while 47.3% were process innovators; 52% of grants-only recipients were product innovators while 39.6% introduced new process; 76.2% of both grant and tax credits recipients introduced new product while 55.7% were process innovators; and 20.5% of firms that did not receive any public support were product innovators while 15.0% were process innovators (see Table 3.2).

3.5.4 Covariates used in propensity score estimation

To determine the probability of firms' participation in each of the three public supports, the so-called propensity score, we estimated logit regressions based on a set of relevant observable covariates. The choice of covariates is based on some exogenous factors that may influence participation in policy intervention as well as the target variable, in this case innovation (Caliendo and Kopeinig, 2008). Included as covariate is firm size measured by log employment to capture potential firm size variations in the effects of public support across sub-groups of firms. Moreover, firm size can serve as potential proxy for the likelihood of being financially constrained. We also control for log employment squared. Vanino et al. (2019) for example, show that both firm size and productivity determine the likelihood of participating in publicly funded research projects. Hence, log labour productivity is also included since it is likely to be correlated with the skills level of workers employed.

At the same time regulations and innovation support programmes may be specifically targeted at SMEs. Included also as a covariate is an export dummy which may reveal a funder's disposition to offer grant support to firms active in international markets, possibly characterized by higher productivity levels with higher potential for innovation (Bernard and Jensen, 1999; Melitz, 2003). We also include firms' external collaborations to control for the extent of firms' external knowledge sourcing activity for innovation (Roper et al., 2008; Battisti et al., 2015) and the potential effect of external knowledge spillovers (Laursen and Salter, 2006). For example, Roper et al. (2008) find evidence of a complementarity relationship between public funding for innovation and firms' ability to benefit from external knowledge sources. Firms require certain resource capabilities to participate successfully in different types of policy instruments, and for effective and efficient utilization of knowledge. We therefore include the scope of firms' skills base and a degree dummy to account for the extent of firms' knowledge utilization capacity (Roper et al., 2008). Moreover, the adoption of technology is affected by the degree that a certain innovation is related to the base of the pre-existing knowledge of its potential users (Cohen and Levinthal, 1990, p.148). A firm's industry or geographic location may impede or strengthen its reaction to certain policy instruments. For instance, high quality research institutions may be concentrated in certain regions within a country such that focal firms may be able to access unique and highly specific knowledge (Intarakumnerd and Goto, 2018). Similarly, regulations and public funding programs may be targeted at specific industries or regions. Time dummies are also included to control for any common macroeconomic effect on firms' innovative prospects. Finally, included as control is an indicator measuring the scope of innovation objectives which drives firms' innovation decisions. Thus, each variable in the treatment participation equation articulates our effort to account for all possible criteria that public agencies may use for the targeting of their grant recipients. Two interaction terms (i.e., productivity with employment and productivity with export) were also included to enhance matching of treated and control observations.

3.5.5 Propensity scores matching results

In order to account for the heterogenous likelihood of treatment participation for firms with different characteristic, we estimate a separate propensity score for each of the three participation scenarios described in section 3.6.2. In Table 3.3 we report the propensity score estimation results stemming from the linear logit models for the general sample. We particularly observe that, in respect of tax only vs. no support (column 2), low productivity, exporting firms with broad scope of external collaboration, innovation decision drivers, and a broad skills base are likely to participate in tax only support. In respect of grant only vs. no funding (column 4), we observe that small, exporting firms with broad scope of external collaboration, broad innovation objectives and skills base are likely to participate in grant support only.

Interestingly, in addition to being a small firm, all the factors that determine participation in tax incentives only also determine participation in policy mix (column 6). Meanwhile, firms' skills base, breadth of innovation objectives, external collaboration and exporting prove to be critical determining factors in participation in public funding (i.e., participation in either tax only, grant only or both).

3.5.6 Balancing test after matching

Standardized differences and variance ratios comparing covariates between treated and control firms in the matched samples are reported in Table 3.4. There is no rule regarding how much covariate imbalance is acceptable in propensity score matching. Although imbalance in some covariates is expected, balance in theoretically important covariates is more crucial than balance in covariates that are less likely to impact the study outcome variable. Proposed maximum standardized differences for specific covariates range from 10 to 25 percent (Austin 2009). Our test results in Table 3.4 indicate that all the variables in our models improved the level of balance and they are all less than the 25% cut off. The standardized differences in the match samples are all close to zero and the variance ratios of all the continuous covariates are close to one. Indeed, the largest absolute standardized difference observed in our matched samples is that of productivity in grant only model (0.09).

Table 3.1: Variables Correlation coefficients

	Variable	Obs.	1	2	3	4	5	6	7	8	9	Tax only (obs: 41,452)	Grant only (obs: 40441)	Both tax and grant (obs: 40,554)
1	Product innovation (0/1)	42,323	1									0.211	0.075	0.149
2	Process innovation (0/1)	42,323	0.398	1								0.158	0.149	0.123
3	Employment (logged)	42,323	0.049	0.062	1							0.033	0.005	-0.007
4	Lab. Productivity (logged)	42,273	0.043	0.033	0.068	1						0.028	-0.003	-0.042
5	Skills base (0-6)	42,323	0.336	0.263	0.209	0.121	1					0.232	0.090	0.153
6	Innovation objective (0-12)	42,323	0.552	0.444	0.093	0.055	0.474	1				0.229	0.113	0.151
7	Collaboration (0-10)	42,323	0.409	0.331	0.067	0.015	0.378	0.614	1			0.184	0.124	0.202
8	Degree (0/1)	37,802	0.243	0.185	0.139	0.084	0.480	0.405	0.284	1		0.150	0.056	0.099
9	export (0/1)	42,323	0.245	0.157	0.104	0.234	0.330	0.299	0.189	0.280	1	0.183	0.048	0.131

Table 3.2: Descriptive statistics across treatment participation

	Full Sample			No support (0/1)			Tax incentive only (0/1)			Grant only (0/1)			Both tax and grant (0/1)		
	# firms	Mean	SD	# firms	mean	SD	# firms	Mean	SD	# firms	Mean	SD	# firms	mean	SD
Product innovation (0/1)	42,323	0.230	0.421	40,062	0.205	0.404	1,390	0.691	0.462	379	0.520	0.500	492	0.762	0.426
Process innovation (0/1)	42,323	0.168	0.374	40,062	0.150	0.357	1,390	0.473	0.499	379	0.396	0.490	492	0.557	0.497
Employment (logged)	42,323	4.182	1.478	40,062	4.174	1.481	1,390	4.442	1.360	379	4.251	1.576	492	4.084	1.407
Lab. Productivity (logged)	42,273	4.456	1.274	40,017	4.455	1.271	1,385	4.651	1.160	379	4.422	1.197	492	3.969	1.689
Skills base (0-6)	42,323	1.116	1.635	40,062	1.009	1.556	1,390	3.081	1.812	379	2.470	1.860	492	3.207	1.834
Innovation objective (0-12)	42,323	4.083	5.100	40,062	3.739	4.975	1,390	10.16	2.931	379	9.575	3.866	492	10.644	2.428
Collaboration (0-10)	42,323	1.123	2.231	40,062	0.980	2.109	1,390	3.186	2.577	379	3.715	2.926	492	4.972	2.610
Degree (0/1)	37,802	0.549	0.498	35,541	0.527	0.499	1,390	0.919	0.273	379	0.802	0.399	492	0.953	0.211
Export (0/1)	42,323	0.286	0.452	40,062	0.263	0.440	1,390	0.718	0.450	379	0.480	0.500	492	0.795	0.404

Table 3.3: Logit estimation results for treatment participation – Full sample

	Tax only		Grant only		Both	
	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
Employment	-0.0457	(0.1460)	-0.435*	(0.202)	-0.948***	(0.2390)
Employment ²	-0.0252	(0.0135)	0.0450**	(0.0149)	0.0121	(0.0241)
Lab. Productivity	-0.263*	(0.1030)	0.0449	(0.1440)	-0.993***	(0.1390)
Skills base	0.212***	(0.0181)	0.136***	(0.0323)	0.197***	(0.0318)
Innovation objective	0.139***	(0.0091)	0.115***	(0.0192)	0.101***	(0.0201)
Collaboration	0.345***	(0.0399)	0.448***	(0.0747)	0.692***	(0.0778)
Collaboration ²	-0.0345***	(0.0048)	-0.0293***	(0.0080)	-0.0443***	(0.0076)
Degree	0.833***	(0.1110)	0.179	(0.1590)	1.116***	(0.2330)
Export	0.958***	(0.2710)	0.962*	(0.4060)	1.610***	(0.4080)
YEAR2016	-0.294***	(0.0762)	-1.066***	(0.1360)	-0.639***	(0.1290)
YEAR2018	-0.151*	(0.0715)	-0.842***	(0.1270)	-0.379**	(0.1260)
Sectors: X^2 (p-value)	262.54	(0.0000)	44.24	(0.0000)	144.74	(0.0000)
Regions: X^2 (p-value)	44.74	(0.0000)	16.2	(0.1339)	48.66	(0.0000)
Interaction terms: X^2 (p-value)	8.51	(0.0142)	4.84	(0.0889)	20.93	(0.0000)
Intercept	-5.318***	(0.5220)	-4.001***	(0.7210)	-2.192**	(0.7150)
Observations	36882		35876		35989	
Pseudo R^2	0.276		0.171		0.414	
log likelihood	-4272.01		-1741.36		-1523.28	

Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05.
χ^2 values indicate test on joint significance of industry dummies, of regional dummies and of the two interaction terms (log labour productivity*log employment and log labour productivity*export)

Table 3.4: Covariates balance test after propensity score matching

Covariates	Tax only		Grant only		Both tax and grant	
	Mean diff.	Var. ratio	Mean diff.	Var. ratio	Mean diff.	Var. ratio
Employment	0.02	1.01	0.01	1.00	-0.02	1.02
Employment ²	0.02	1.03	0.01	0.99	-0.02	1.12
Lab. Productivity	-0.01	1.05	-0.09	1.17	0.01	0.88
Skills base	-0.01	1.01	0.03	0.98	-0.07	0.96
Innovation objective	-0.06	0.85	-0.06	0.98	-0.06	1.00
Collaboration	-0.02	0.98	0.02	0.98	0.00	1.01
Collaboration ²	-0.02	1.02	0.01	0.97	0.00	1.03
Degree	-0.04	.	0.03	.	-0.03	.
Export	0.07	.	-0.03	.	0.02	.
YEAR 2016 dummy	0.00	.	0.03	.	-0.03	.
YEAR2018 dummy	0.00	.	-0.09	.	-0.03	.
No. Treated	1,385		379		492	

3.6 Empirical results and discussion

We investigate the heterogenous impact of public support on the innovation performance of participating firms. First, we estimate the general effect of tax-incentives-only, grants-only and a policy mix for the total sample of firms, providing several tests to substantiate the robustness of the results. Secondly, we explore the heterogenous impact across different characteristics including firm size, firms' productivity, technology intensity, knowledge intensity, and industrial distribution.

3.6.1 Policy impact on innovation – general effect

Table 3.5 presents the overall results for the full sample. The results indicate that both policy mix and tax-incentives-only led to output additionalities in respect of product innovation and process innovation, confirming the crowding-in effect theory which suggests that public support to the private sector leads to increase in the performances of treated businesses. Specifically, there are 10.2 percentage points more firms that introduced new and significantly improved product among the firms which received R&D tax-incentives-only than firms in the control group (i.e., non-public supported firms). In terms of process innovation, firms which received tax-incentives-only are 5.6 percentage points more likely to declare having introduced a new process than those in the control group. Our results appear to be consistent with those provided by the body of literature that report evidence of significant output additionality among R&D tax-incentives-only receiving firms (e.g., Czarnitzki et al., 2011; Cappelen et al., 2012; Aralica and Botrić, 2013). Unfortunately, in consensus with Petrin and Radicic (2023), we do not find significant evidence to suggest that grants-only promotes output additionality in treated firms. We will however not be quick to judge grants-only as ineffective since the insignificant result observed here could be as a result of a turn-around time lag between innovation input and innovation output. Direct grant funded projects are often long-term in nature, which implies that any innovation outcome that can be realised from such projects may require considerable time period to be observed. Nonetheless, our sub-sample analyses indicate that grants in isolation promote product innovation in LKIS firms and process innovation in low-tech manufacturing firms.

Our last treatment group concerns the possible interaction between R&D grants and R&D tax incentives. While we find a significant effect of tax incentives and no significant effect of grants on innovation, the effect of the interaction between the two policy tools is always significant and remarkably high. For instance, 11.2 percentage points more firms in the policy mix recipients' group than the control group undertook process innovation, while only 5.6 percentage points more firms in the tax-incentives-only treatment group undertook process innovation than the control group. Similarly, firms participating in the policy mix are 16.1 percentage points more likely than firms in the control group to introduce new products, while tax-incentives-only recipients are 10.2 percentage points more likely than the control group to introduce new products. However, we caution readers that a comparison of magnitude should be done with care since the treatments are binary variables. Nonetheless, this evidence suggests a strong complementarity between R&D tax incentives and R&D grants which is coherent with the theoretical hypothesis made by Flanagan et al. (2011) and Rogge and Reichardt (2016) about the complementarity effect of mixing policy instruments. Thus, under some circumstances, a mix of innovation policy interventions may be more effective in stimulating innovation activities than administering interventions in isolation: in our case, R&D grants may only be effective for innovation output if they are combined with tax incentives.

The results for our entire sample are consistent and robust to additional tests where we used coarsened exact matching with propensity score matching technique with very similar ATT's (see column 5 – column 7 of Table 3.5). These have consistent statistical significance when considering all the three treatment models.

Table 3.5: Impact of public support participation on innovation performance – Full sample and robustness

	Full sample – PSM			Full sample – CEM with PSM		
	Tax only	Grant only	Both	Tax only	Grant only	Both
Product Innovation	0.102***	0.0317	0.161***	0.100***	0.0204	0.163***
	(0.018)	(0.035)	(0.034)	(0.019)	(0.039)	(0.034)
Process innovation	0.0563**	0.0317	0.112**	0.0726***	0.0585	0.110**
	(0.020)	(0.035)	(0.037)	(0.021)	(0.036)	(0.038)
No. Treated	1,385	379	492	1,314	343	472

Notes: Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05.
Number of Control observations equals number of treated observations.

Meanwhile, research has found that the impact of public support on firms' performance may vary depending on firm specific characteristics (e.g., see Vanino et al., 2019; Czarnitzki and Lopes-Bento, 2014; Dimos and Pugh, 2016). We therefore evaluate the impacts of policy participation on the performance of firms depending on firm size (results reported in Table 3.6), sector-specific characteristics (results reported in Table 3.7) and productivity distribution (results in Table 3.8).

3.6.2 Policy impact across size

Presented in table 3.6 are the results of our analysis of public support effects distributed across small and medium-large firms. Overall, the effect of tax-incentives-only on innovation is similar for both small and medium-large firms – participating firms experiencing between 6% and 9% additionality relative to their untreated counterparts. Similar result by Petrin and Radicic (2023) indicates tax credits promote both product and process innovation among small as well as large Spanish manufacturing firms. While we do not find significant result for grant-only for either small or medium-large, the effect of a policy mix on process innovation is greater for small, experiencing 17.3% additionality, compared to the 12.3% additionality observed among participating medium-large firms. Conversely, the effect of a policy mix on product innovation is greater for medium-large firms, with participation leading to 15.6% additionality compared to the 10.9% additionality for small firms. We recall from Section 2.6.2 that the effect of both tax-incentives-only and grant-only on R&D investment was consistently greater for small than for medium-large firms. Nonetheless, this latter result seems to confirm the general knowledge that large firms are typically technologically more advance than small firms, and therefore have greater capability for transforming innovation input into innovation output, and for higher innovation performance.

Table 3.6: Impact of participation in public support on firms' innovation performance across firm size

	Small firms (10 - 49 employment)			Medium - large firms (50+ employment)		
	Tax only	Grant only	Both	Tax only	Grant only	Both
Product Innovation	0.0930**	0.00592	0.109*	0.0844***	0.0333	0.156***
	(0.032)	(0.056)	(0.052)	(0.022)	(0.046)	(0.041)
Process innovation	0.0507	0.0118	0.173***	0.0592*	0.00476	0.123**
	(0.033)	(0.050)	(0.052)	(0.024)	(0.047)	(0.046)
No. Treated	473	169	248	912	210	244

Notes: Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05.
Number of Control observations equals number of treated observations.

3.6.3 Policy impact across industry

Overall, the effect of tax-incentives-only and policy mix on innovation is similar for both service and manufacturing, participating firms experiencing between 8% and 17% additionalities, albeit different aspects of innovation being emphasised by similar policy instrument. For instance, while tax-incentives-only is effective for both product and process innovation in manufacturing, it is effective for only product innovation in the service industry. Conversely, policy mix is effective for both product and process innovation in service firms, and effective for only product innovation in manufacturing firms. We do not observe significant result for process innovation in manufacturing businesses, which may be due to the fact that many manufacturing firms have production engineers whose job would be to improve processes (Stinchcombe, 2000); Hence grant support may not make any significant difference in their process innovations. Similar result was found by Petrin and Radicic (2023) indicating positive effect of tax credit, and no effect of grant, on both product and process innovation among participating Spanish Manufacturing businesses. Bérubé and Mohnen (2009) also record that Canadian manufacturing firms that received a mix of grants and tax credits experienced a stronger effect on product innovation than they experienced from tax credits in isolation.

Distinguishing between high-tech and low-tech manufacturing industries, tax-incentives-only impacts innovation only among high-tech manufacturing, recording 12.3% and 14% additionality respectively for product and process innovation. Our results thus highlight the importance of tax-incentives for product innovation in high-tech businesses. Product innovation often require high internal innovative capability on the part of the firm. Most tax incentive schemes run for a long period of time and thus provide a reliable base for long-term financial planning and R&D decisions (Appelt et al., 2016), which implies that high-tech firms are able to integrate tax deduction into their innovation decisions and invest more into their innovation activities, subsequently increasing their innovative capacity and performance. Meanwhile, different technological opportunities, varying degrees of ACAP, knowledge diffusion and spillover effects impact the manner in which firms organise and benefit from their innovation activities (Castellacci and Lie, 2015). High-tech businesses generally exhibit high degree of ACAP for considerable benefit from knowledge diffusion and spillovers. For instance, a recent econometric analysis by Roper and Nana-Cheraa (2023) indicates that intra-sector collaboration significantly impacts new-to-firm product innovation at the sectoral level. The authors econometric analysis was sequel to a sectoral ACAP profiling, which placed high-tech sectors in the topmost quartile, and among the highest in rank in terms of intra-sector collaboration. These attributes of the high-tech business imply greater likelihood of their innovation success.

In contrasts to tax-incentives-only promoting innovations only in high-tech sectors, participation in grant-only rather promotes only process innovation in low-tech manufacturing, participating firms experiencing 25.5 percentage points additionality relative to their untreated counterparts. Since low-tech businesses are generally low in terms of R&D intensity, grant support helps them to build capability for subsequent innovation. Policy mix on the other hand promotes only product innovation, although the effect is larger for low-tech manufacturing (25.8%) than for high-tech (20.4%). These latter results highlight the importance of public support, for improving processes aimed at maximising efficiency, in low-tech businesses which are normally classified as low in terms of R&D intensity and technological innovation.

Meanwhile, the effect of tax-incentives-only on product innovation is larger for Less-KIS, firms experiencing 12.6% additionality, compared to 9.6% in KIS. Participating in grant-only has no impact on innovation in KIS, but promotes product innovation in Less-KIS, with participating Less-KIS firms experiencing 18.9% additionality relative to their untreated counterparts. Conversely, policy mix has no impact on innovative in the Less-KIS, but promotes both product and process innovation in KIS, participating KIS reporting 10.7% additionality in product innovation and 15.7% additionality in process innovation. These findings seem to suggest that it is easier for less-KIS businesses to create new products than new processes.

3.6.4 Policy impact across productivity distribution

Finally, public support impact across firm productivity distribution is reported in Table 3.8. The results indicate a significantly positive effect of both tax-incentives-only and a policy mix on product innovation among firms in the 2nd and above quartiles of the productivity distribution. Tax-incentive-only support seems to be the only intervention that promotes process innovation and even that, it is among the highest productive firms: 7.2% and 9.6% additionality respectively for participating firms in the 3rd quartile and 4th quartile of the productivity distribution. We recall from Section 2.6.4 that the least productive firms (i.e., firms in the 1st quartile of the productivity distribution) consistently exhibited the highest R&D input additionality in all the three policy interventions. Unfortunately, we do not find the same pattern in terms of innovation output additionalities. This seems to suggest that participating firms are low on innovation productivity alongside production productivity. Thus, low productivity firms are not particularly effective at translating innovation input into innovation output, potentially due to limitation in internal innovative capacity and/or limitation in leadership competence for efficient management of innovation processes to generate innovation outcomes (Gahan et al., 2021).

Table 3.7: Impact of public support participation on innovation performance – manufacturing, service, high-tech, low-tech, KIS and LKIS industries

	Manufacturing			Manufacturing – high technology			Manufacturing – low technology		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Product Innovation	0.103***	-0.0100	0.167***	0.123**	-0.0222	0.204**	0.0720	0.0545	0.258***
	(0.031)	(0.064)	(0.047)	(0.044)	(0.115)	(0.074)	(0.044)	(0.098)	(0.077)
Process innovation	0.0953**	0.0600	0.0632	0.140**	0.1780	0.0741	0.0680	0.255**	-0.0152
	(0.034)	(0.067)	(0.056)	(0.048)	(0.097)	(0.079)	(0.049)	(0.089)	(0.090)
No. Treated	493	100	174	243	45	108	250	55	66

	Service			KIS			Less-KIS		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Product Innovation	0.109***	-0.0243	0.0885*	0.0962***	-0.0987	0.107*	0.126**	0.189**	0.1200
	(0.025)	(0.043)	(0.045)	(0.026)	(0.055)	(0.045)	(0.047)	(0.066)	(0.130)
Process innovation	0.0319	-0.0283	0.161**	0.0833**	-0.0461	0.157**	0.0158	0.1050	0.0400
	(0.026)	(0.044)	(0.049)	(0.028)	(0.059)	(0.051)	(0.047)	(0.068)	(0.144)
No. Treated	814	247	305	624	152	280	190	95	25

Notes: Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations.

Table 3.8: Impact of public support participation on innovation performance across firm productivity (quartiles)

	1st quartile			2nd quartile			3rd quartile			4th quartile		
	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both	Tax only	Grant only	Both
Product Innovation	-0.041	0.034	-0.013	0.160***	-0.075	0.295***	0.193***	-0.081	0.152**	0.132***	-0.035	0.181*
	(0.057)	(0.082)	(0.073)	(0.037)	(0.071)	(0.064)	(0.033)	(0.063)	(0.059)	(0.035)	(0.075)	(0.076)
Process innovation	0.0001	-0.023	0.013	0.063	0.0001	0.134	0.072*	-0.027	0.080	0.096**	0.0001	0.108
	(0.056)	(0.072)	(0.074)	(0.043)	(0.059)	(0.071)	(0.036)	(0.067)	(0.063)	(0.037)	(0.071)	(0.082)
No. Treated	172	88	159	349	94	112	456	111	138	408	86	83

Notes: Robust standard errors are in parentheses. ** * p< 0.001, ** p<0.01, * p<0.05. Number of Control observations equals number of treated observations.

Table 3.9: Symbolic representation of innovation outputs additionality research results

	Product innovation			Process innovation		
	Tax only	Grant only	Both	Tax only	Grant only	Both
Full sample	+	(+)	++	+	(+)	++
Small	+	(+)	++	(+)	(+)	++
Medium-large	+	(+)	++	+	(+)	++
Manufacturing	+	(-)	++	+	(+)	(+)
High-tech manufacturing	+	(-)	++	+	(+)	(+)
Low-tech manufacturing	(+)	(+)	++	(+)	+	(-)
Services	+	(-)	$+^{<}$	(+)	(-)	++
KIS	+	(-)	++	+	(-)	++
LKIS	+	+	(+)	(+)	(+)	(+)
Productivity frontiers						
1st quartile	(-)	(+)	(-)	(+)	(-)	(+)
2nd quartile	+	(-)	++	(+)	(+)	(+)
3rd quartile	+	(-)	$+^{<}$	+	(-)	(+)
4th quartile	+	(-)	++	+	(+)	(+)

Notes:
\+ means significant positive effect
++ means significant positive effect of mix is larger than effect of both tax-only and grant-only
$+^{<}$ means significant positive effect of mix that is smaller than the effect of either tax in isolation
(+) means insignificant positive effect
(-) means insignificant negative effect.

3.7 Conclusion

In Chapter 3, we analyzed the innovation output additionalities of UK innovation policy mix which has received little attention in the literature. Empirical studies on policy mix predominantly consider its impact on innovation input. This is despite the fact that firms often receive mixes of public supports which tend to interact and influence the effect of one another. The central argument in the literature has been the need to analyse the joint effect of support instruments in mixes to avoid under- or over-estimation of individual instrument effect. The main focus of this study is therefore to provide an evaluation of the effectiveness of public policy mix (i.e., consisting of R&D tax incentives and R&D grants) in creating additionalities in supported firms in terms of their product and process innovation prospects. We also provide insight into the output additionalities of the individual policy instruments.

The general consensus in the literature regarding the limitation in the number of empirical studies on innovation output impact of policy mix has been on the lack of availability of datasets with comprehensive information on both firms' innovations and the variety of supports they receive (e.g., Guerzoni and Raiteri, 2015; Rogge and Reichardt, 2016; Lenihan and Mulligan, 2018). With the help of the UK Innovation Survey which provides details on various firm-level innovation indicators as well as information on whether firms received R&D tax incentives or R&D grants, we are able to provide a comprehensive evaluation on the effectiveness of public supports to the private sector focussing on the experience of the UK.

Our initial evaluation of public supports impacts involved the use of a full sample of 42,323 observations. We then considered the variation in the effects of public supports across sub-groups of firms depending on size, knowledge and technology intensities, industry, and firm productivity. Table 3.9 provides a symbolic summary of all the results produced in this study (see Table 3.5 to Table 3.8 for the actual estimated ATT's and their respective significance level). Generally, the empirical evidence seems to suggest that R&D grants in isolation have no significant output additionalities effect, while tax incentives are associated with promoting output additionalities in participating firms with particularly higher impact on product innovation than process innovation. Since accessing tax incentives is not conditional on the type of innovation project, it appears that tax incentives indeed induced participating firms to invest more private funds on projects thereby increasing the efficiency with which knowledge acquired is transformed into innovation output and thus, accelerating projects completion. That is, tax incentives in isolation complement firms' investment efforts in attaining innovation output.

The insignificant result recorded for grants may occur as direct grants partially or fully crowd-out private innovation effort and thereby compromise the volume of investment and subsequently, limiting the potential efficiency with which acquired knowledge could be transformed into innovation output. Moreover, direct grant funded projects are often long-term in nature which may imply that any innovation outcome resulting from such projects may take time before becoming visible in our data. Unfortunately, our data does not allow evaluation of how participation in funding impact innovation over time. Future UK Innovation Surveys that permit panel analysis may help provide insight into the long-run innovation impact of direct grants. In terms of policy mix, we find a complementary effect of tax incentives on grants when the two policies interact. That is, the interaction of grants with tax incentives within a mix creates stronger additionalities in both product and process innovation than the output additionality generated by tax incentives in isolation (bearing in mind that grants in isolation do not show evidence of significant impact on innovation). This complementarity effect of tax incentives on grants is consistent across all the evaluation results of this study. From a policy point of view, the stronger interaction effect between grants and tax incentives seems to confirm the importance of integrating both support tools for the purpose of achieving high innovation performance among firms. This is particularly needful for projects funded through only direct public support since there seems to be a loss of effectiveness when direct support is administered in isolation.

Exploring the policy mix impacts across the various firm characteristics, we find that the policy mix effect on product innovation is higher for medium-large firms than for small firms. Thus, although we record a significant product innovation additionality for small firm, the size of the effect does not match up with that of medium-large firms. This evidence seems to confirm the advantages that large firms often have over small firms in regards to ease of access to the capital market, and economies of scale and scope, or the fact that small firms are often constrained in terms of internal capabilities for the transformation of generated knowledge into product innovation which is mostly technical in nature. Nonetheless, the policy mix effect on process innovation is higher for small firms than for medium-large firms. Higher product innovation impact of policy mix is also found for firms in the manufacturing, low-tech manufacturing, KIS, and for medium-large firms. Meanwhile, both small and service firms may need policy mix in order to observe additionality in both product and process innovation. Finally, while process innovation impact is stronger for smaller than for medium-large firms, significantly positive process innovation impact is found only for firms in KIS and service industries. Meanwhile, there is no significant evidence to indicate that public funding promote innovation in low productivity firm. The empirical evidence across the multiple firm specific characteristics considered in this study appears to suggest that different firms respond differently to different public supports including policy mix.

From policy and managerial point of view, the results seem to suggest that in comparison with grants, tax incentives only are effective in promoting both product and process innovation in treated firms. The effectiveness of tax incentives only is more pronounced particularly for product innovation irrespective of firm size, industry, technology or knowledge intensity level, and firm productivity level. Secondly, a mix of tax incentives and grant supports create enhanced innovation additionalities than the individual supports in isolation, particularly for product innovation in manufacturing (both high-tech and low-tech), KIS firms, small and medium-large firms.

By providing an empirical application of the policy mix concept, this study contributes to our understanding of the effectiveness of public support in promoting innovation output additionalities. This extends prior studies which mainly focussed on policy impacts on the innovation input. Our evaluation therefore contributes to the limited literature on the public policy mix and innovation output link, particularly with regards to the UK public supports. Secondly, the study extends previous studies by providing insight into the innovation impacts of tax incentives and grants in isolation, as well as the impact of their interaction. This contributes to the argument in the literature regarding substitutability or complementarity effects from the instrument interaction. Our overall result is in favour of a complementary or synergistic effect when policies are administered in mixes. One novel aspect of this study's contribution is the consideration of the differing effect of tax incentives only, grants only and a mix of both across multiple firm-specific characteristics, and over product and process innovation. Although few studies have examined the impact of individual policies or policy mix for specific types of firms including size, and manufacturing, there is no study, to the best of our knowledge, that provides a comprehensive evaluation of the implications of public supports for different industries, knowledge and technology intensities, over firm sizes and the productivity distribution. Our study therefore extends the current literature.

3.8 Limitations and future research

Although our study makes several contributions to the innovation policy literature, it is not without limitations. First, our analysis focussed on the distinction between product and process innovations only. For this reason, it remains unclear how different innovation strategies are impacted by policy interventions. Future research could use the same dataset to investigate other innovation outcomes such as radical or incremental innovations, organisation innovations, such as changes in marketing strategies or ways of organising, or innovation success in terms of productivity or employment gains. Another limitation of our study is the fact that, our dataset does not allow us to analyse the amount of support that firms receive. Thus, analysis of how different intensities of public support impact firm innovation is infeasible in this current study. This remains a critical challenge since it is unclear exactly how much public support is enough to achieve a desirable innovation performance. Exploring administrative data on the amount of R&D tax incentives and direct R&D supports available to firms may help with the analysis of when government may be under- or over-subsidising. Meanwhile, we found no significant innovation effect for R&D grants in isolation although the coefficient was positive. The approach taken by this current study focused on public supports and their additionality effects in one period, and thus does not examine the long-term effect of supports. Our data is also constrained concerning information on the different phases of the innovation value chain. We are thus unable to examine whether the general insignificant output additionality effect of R&D grants is because supported firms may be at the ideation or implementation phase of the innovation value chain. Access to datasets with comprehensive information on the various supports that firms receive as well as information on firms' innovation activities, including the various phases of the innovation value chain may present an excellent analytical advantage for empirical studies. Finally, we dwelt on the group of firms in our sample that did not receive any public support for the calculation of the counterfactual scenario for our treated observations. This approach does not directly examine the performance of policy mix vis-à-vis tax incentives or grants in isolation. Future research could extend this research by using participation in tax-incentives only and grants only as two distinct control groups for the policy mix treatment.

Chapter 4

4 The Causal effect of strategic human resource management systems on firm innovation

Abstract

This study uses a novel data match to examine the relationship between high-performance work systems and innovation. The study specifically proposes and examines the direct causal effect of three components of HRM systems: human-capital-enhancing, motivation-enabling and opportunity-enabling on product, process and organisation innovation. The results indicate that human-capital-enhancing practices have a positive effect on both process and organisation innovation. Motivation-enabling practices impact only on process innovation, while opportunity-enabling practices impact on both product and organisation innovation. The results also indicate that service firms and medium-large firms exhibit similar pattern in terms of innovation gain from the adoption of HRM systems. Manufacturing firms and small firms also show a similar innovation gain pattern. Practical implications and avenues for future research are discussed.

4.1 Introduction

Human Resource Management (HRM) researchers have over the past couple of decades explored the importance of HR practices in explaining organizational performance differences (Becker and Huselid, 2006; Batt and Colvin, 2011; Glaister et al., 2018; Henley, 2022). The conceptual and empirical work related to the unique influence of HRM practices on organizational performance has progressed far enough to suggest that the role of HRM is crucial. However, while a considerable number of studies have examined the link between HRM and firm-level performance outcomes such as productivity, employee turnover, firm growth and corporate financial performance (Batt and Colvin, 2011; Huselid and Becker, 2011; Jiang, Lepak et al., 2012; Patel et al., 2013), the body of work in terms of the relationship between HRM and firm innovation remains relatively small, and rarely considers the UK context. Moreover, the few prior studies that examined the link between HRM and firm innovation only conclude an association between the use of HRM practices and higher levels of innovation, with very few establishing a causal link (e.g., Beugelsdijk, 2008; Chang et al., 2013; Liu et al., 2017). This is despite the fact that innovation is frequently cited as a fundamental for firms to achieve competitive advantage, suggesting that elements that impact firm innovation performance are important areas for investigation. This chapter is motivated by the fact that there is limited research on how HRM practices impact firm-level innovation, particularly in the context of the UK economy. The motivation of the chapter is therefore, to examine possible innovation impact of HRM, focusing on the UK.

To survive intensifying market competition, firms have turned to effective utilization of their human capital to attain high level performance (Kaufman, 2015). It is widely acknowledged that an organization's capability to innovate is closely linked to its ability to utilize its human capital. An organization's human capital which is created from the collective interaction of its workforce skills, knowledge, abilities and other characteristics (Ployhart and Moliterno, 2011) represents a vital input for the organization's strategic business plan development and execution (Huselid, 1995). Several literatures not only suggest human capital to be significant, but also as among the most strategically relevant resources for other organizational performance (e.g., Barney, 1991; Huselid, 1995; Becker and Gerhart, 1996; Coff and Kryscynski, 2011). In another vein, human resource management (HRM) has been defined as the management of work, people, and knowledge in an organization towards desired ends (Wright and McMahan, 1992). Similarly, organizations' capacity to innovate is conceptualised as residing in the capabilities, behaviour and motivation of their people (Gupta and Singhal, 1993), which implies HRM is involved in the entire innovation process since employee input is required for the development and implementation of innovation (Jimenez-Jimenez and Sanz-Valle, 2008).

Traditional HRM research has focused on exploring the impact of individual best HR practices on organizational performance, while strategic HRM researchers emphasise bundles or systems of HR practices in explaining the influence of HRM on organizational performance (e.g., Boxall and Purcell, 2003; Delery and Doty, 1996; Comb et al., 2006; Delaney and Huselid, 1996; Jiang, Wang et al., 2012). The assumption underlying the individual best practice approach is that there is potential for organizations to improve their performance if they implement certain best HR practices in isolation (Wood, 1999). The bundle/integrated approach on the other hand emphasises the need to integrate the operation of bundles of individual HR practices in a complementary manner (Wood, 1999; Boxall and Macky, 2009;

Boxall and Purcell, 2022). Some of these integrated HR practices have been labelled high-commitment work systems (De Saa-Perez and Díaz-Díaz, 2010), high-involvement work systems (Martínez-del-Río et al., 2012; Li et al., 2018) or high-performance work systems (Shipton et al., 2006). The general view is that HR practices, either individually or in systems, have a positive impact on organizational performance (Lado and Wilson, 1994; Huselid, 1995; Laursen and Foss, 2003). However, the literature suggests that HR practices have better effect on firm performance when they are adopted in a bundle rather than as individual components (Laursen and Foss, 2003; Laursen and Mahnke, 2001). In particular, HRM systems intended to enhance employees' abilities, skills, knowledge, motivation, and opportunity to contribute have been found to impact positively on firm performance (Huselid, 1995; Gong et al., 2009; Lee et al., 2019; Yao et al., 2022). Additionally, the effect of HRM is best understood by evaluating systems of HR practices rather than examining HR practices individually (e.g., Liao et al., 2009; Lee et al., 2019).

Current strategic research suggests organisations can impact performance by using HRM practices to enact favourable influence on employees' actions. Another stream of argument in the literature suggests that HRM impacts performance by contributing to employee competencies, i.e., their knowledge, skills and abilities (Yao et al., 2022. Although employees contribute to firm performance through both their competence and actions, researchers tend to focus on one perspective in examining how HRM impacts performance. Nonetheless, some strategic HRM scholars have taken a different approach by drawing upon the ability-motivation-opportunity (AMO) framework to explain the relationship between HRM and organisational performance (e.g., Demortier et al., 2014; Yao et al., 2022; Minbaeva and Navrbjerg, 2023). The rationale behind the AMO framework suggests employee performance is dependent on three vital components: ability, motivation and opportunity to participate. It can be argued that the AMO framework acknowledges both the behavioural and human capital perspectives on performance, but then introduces a third component which is opportunity for employee participation. In other words, opportunity for participation serves as an "ecosystem" where both human capital and employees' productive behaviours thrive to impact performance. In a nutshell, the AMO framework presents the opportunity to examine the relationship between HRM and performance through the lens of multiple perspectives simultaneously, thereby offering a broader and more comprehensive picture (Jiang, Lepak et al., 2012). This research further provides insight that addresses a limitation in the literature regarding whether to emphasise all or different combinations of the AMO components depending on firm context.

The current research focuses on HRM as a strategic lever for significant firm-level innovation. Based on the behavioural perspective of HRM, human capital theory, and the resource-based view of the firm, we delineate three components of HR systems, namely, human-capital-enhancing HR practices (HEH), motivation-enabling HR practices (MEH) and opportunity-enabling HR practices (OEH) and examine their respective influence on firm-level innovation. By doing so, we make the following contributions to the literature. First, we provide a novel contribution to the literature in the sense that this current study introduces a new data match which allows us to extend previous literature by establishing a causal link between HRM systems and firm innovation. Previous literature on the HRM and innovation link uses cross sectional data and focuses on associations between individual HRM practices or systems of practices on one side and innovation on the other. With the help of a new data match which is based on time differences for measures of innovation and HR practices, this study is able to extend the current literature and contribute to the causal understanding of how systems of HRM practices influence innovation outcomes. Second, we contribute to the limited literature on the HRM and innovation link, and the literature on strategic HRM systems as levers for developing competitive advantage through innovation. The main research question of this study was to examine the link between HRM and firm-level innovation since little attention has been given to this relationship in the literature. Moreover, according to the strategic HRM literature, the effects of HRM on performance are better understood when practices are examined as systems rather than on individual bases. Third, while it is argued in the literature that consistency within HRM system configuration is critical for maximum impact on performance, so is the fact that different kinds of innovations may potentially require different sets of HRM systems. This study thus provides a theoretical explanation of how different components of HRM systems may influence different kinds of innovations, and provides empirical evidence on specific HRM systems that can have a positive impact on specific types of innovation. Specifically, the study uses three objective measures of innovation instead of the subjective perceptual measures that are often used in the literature to provide insight into the fact that different innovation aspiration requires different sets of HR systems. This evidence is not surprising since the data used by this study suggests innovators are slightly different in terms of product, process and organisation innovation. Moreover, these dimensions of innovation are different in terms of the level of technicality: while product innovation is more technical and involves technological development, process innovation is more about improvement in process or equipment used in producing the product. Organisational innovation on the other hand is more about soft innovation involving improvements in work organisations. Another novel contribution of this study is the fact that it provides insight into the heterogenous effects of HRM systems based on firm specific characteristics. Previous studies have rarely considered how contextual factors such as dimensions of industries or firm size may define differentials in HRM impacts across such dimensions. Although a few studies have examined the impact of HRM for specific types of firms including manufacturing (Sung and Choi, 2018; Chang et al., 2013) and knowledge intensive firms (Collins and Smith, 2006), there is no study, to the best of our knowledge, that has provided a comprehensive analysis of the implications of systems of HR practices for different industries and firm sizes. Different innovation strategies and other firm-specific contexts might dictate emphasis on different combinations, as supposed to all aspects of the AMO model. This study therefore extends the current literature by providing a comprehensive evaluation of the impact of HRM systems across various innovations over industries and firm sizes. Overall, the result of this study evidence the strategic value of HRM systems and have management practice implications.

The remainder of Chapter 4 is structured as follows. Section 4.2 presents a review of the empirical literature on the relationship between HRM and innovation. Section 4.3 provides a discussion of the theory and mechanisms linking HRM to innovation. Also presented in this section are the research hypotheses development. The research methodology and data description are in Section 4.4. The results are detailed in Section 4.5. Section 4.6 concludes the chapter, providing detailed discussion of key findings. Research limitations and avenues for future research are discussed in Section 4.7.

4.2 Literature on the HRM and firm innovation link

There is a limited number of empirical works on the HRM and innovation link. However, the few that have done so mostly established relationships of association between the two and not a causal effect of HRM on innovation (e.g., Beugelsdijk, 2008; Chang et al., 2013; Liu et al., 2017). Nonetheless, these studies which have been conducted across various countries and levels of analysis seem to have a consensual conclusion of a positive influence of HRM on innovation whether HRM practices are examined on individual bases or as a bundle of practices.

While some studies examined the direct relationship between HR practices and innovation, other researchers in the cause of establishing a link between the two have used mediators such as trust, cooperation, shared codes and language, and knowledge exchange and combination

(Collins and Smith, 2006), knowledge management (Lopez-Cabrales et al., 2009), absorptive capacity (Chang et al., 2013), internal commitment and external collaboration (Zhou et al., 2013), internationalization (Walsworth and Verma, 2007), employee proactivity (Lee et al., 2019), and dynamic capability (Gahan et al., 2021). In terms of measurement, while some studies use product and administrative innovations, the majority of studies measured innovation through managers' subjective perception of the organizations' ability to introduce new products, or its performance in terms of technology development.

Specific recent studies in the literature that have evaluated the direct influence of HRM practices and innovation include that of Armstrong et al. (2010), James Chowhan (2016), and Andreeva et al. (2017). Specifically, Andreeva et al. (2017) conducted a study on Finnish firms and found a direct link between two HR practices and managers' subjective perceptions of performance in terms of their perceptions of the effect of radical and incremental innovation on net sales. According to the evidence, reward of knowledge behaviour has a positive and significant influence on both incremental and radical innovation, ceteris paribus. Appraisal of knowledge behaviour on the other hand is associated only with incremental innovation, ceteris paribus. Using data from 179 organizations in China, Zhou et al. (2013) found that both commitment-oriented system (which includes selection recruitment, job enrichment, self-managed teamwork, extensive training, job rotation, information sharing, result-based appraisal, and development-oriented feedback) and collaboration-oriented system (which includes formal external learning program with business partners, flexible partnership with autonomous external professionals, long-term personnel alliance with external academic institutions, building extensive social networks, and professional HR outsourcing) have a direct relationship with firm innovation. The authors also found that using both systems simultaneously appear to be detrimental to innovation performance. Armstrong et al.'s (2010) study of Irish companies found that HPWS practices including training and monitoring, recruitment, high pay, and promotion across minority groups are positively associated with product and service innovation. Beugelsdijk's (2008) study on Dutch firms also examined the direct relationship between innovation and individual HR practices. The author concluded that task autonomy, training and performance-based pay are associated with incremental innovations, while task autonomy and flexible working hours are important for generating radical innovations among participating firms. Jimenez-Jimenez and Sanz-Valle's (2008) study of Spanish firms found that HRM systems which include team working, flexible job design and empowerment, long-term and skill-oriented staffing, extensive and long-term training, Broad career opportunities, and behaviour-based appraisal and compensation are associated with organizational innovation. In the same spirit, De Saa-Perez and Díaz-Díaz's (2010) study on firms in the Canary Islands indicates that the use of high-commitment HR systems which includes internal promotion, appraisal for promotion, employee participation, planned training, variable reward, and job security promote process innovation. Meanwhile, Michie and Sheehen (1999) found firms that adopted a system of HPWS consisting of innovative pay plan, teamwork, employment security, job flexibility, and regular information sharing between management and employees are more likely to introduce new technology than firms that use traditional HR practices. Meanwhile, James Chowhan's (2016) longitudinal study on Canadian firms employed the AMO framework and argued that recruitment and selection, and training constituted a skill-enhancing system; direct compensation, promotion opportunity and benefits constituted a motivation-enhancing system; while an opportunity-enhancing HRM system includes HRM practices such as autonomous work, self-directed work groups, flexible job design and information sharing. The evidence from the study suggests each of the three systems has a direct positive relationship with innovation.

Lee et al.'s (2019) study links HRM to innovation using mediating effects. The authors specifically found that individual proactivity mediates a positive relationship between change-oriented HR systems and group innovation among participating Korean firms. That is, an HR system which consists of staffing practices and training programmes with emphasis on enhancing employee creative skills, communication abilities, new knowledge generation and knowledge implementation abilities induces a proactive psychological state among employees which subsequently leads to innovation. The authors also found that while an HR system which consists of performance appraisal and reward enhanced employees' motivation, the system consisting of decision-making empowerment, participation in group decision making, and information sharing provided employees with the opportunity to use their competencies to influence innovation. A recent study by Mehralian et al. (2022) emphasises the mediation role of dynamic capability between HPWS and innovation performance, while innovation culture strengthens the mediation effect. Similarly, Gahan et al. (2021) show that HPWS and leadership competence impact innovation through the formation of organisational dynamic capability. Also, Chen and Huang's (2009) study on Taiwanese firms identified that compensation pay, staffing and employee participation impact managers perceived technological innovations, whereas performance appraisal, staffing and employee participation impact managers' perceived administrative innovation. In both cases, the relationships are fully mediated by the organizations' knowledge management capacity. Wei and Lau (2010) found that alignment of firm's strategies mediates a positive relationship between high performance works systems and innovation among participating Chinese firms. Meanwhile, Lopez-Cabrales et al. (2009) found that unique knowledge mediates a positive link between collaborative HRM practices and managers' subjective perception of product innovation.

Meanwhile, other studies have explored moderating factors such as strategic innovation importance, churn in human resource, and homogeneity of employees' experience with high performance work systems to explain the extent of HRM influence on innovation. For instance, Li et al.'s (2018) study on Canadian firms found a positive relationship between an HRM system consisting of flexible job design, information sharing, problem-solving teams, self-directed teams, gainsharing, and training (which they termed high-involvement work system - HIWS) and firms' innovation in terms of product and process innovation. The positive effect is moderated by the extent of the focal firm's strategic importance of innovation, churn in human resource, and homogeneity of employee HIWS experience. In the same spirit, Liu et al. (2017) found both employee creativity and firm ownership moderates a positive relationship between performance-oriented HR practices (e.g., performance appraisal) and maintenance-oriented HR practices (e.g., employment security) and product innovation in participating Chinese firms. According to the authors, aggregate employee creativity at the firm-level was more strongly related to firm innovation in private-owned enterprises than in state-owned enterprises. Meanwhile, Walsworth and Verma's (2007) study of Canadian workplaces and employees found that internationalization moderates a positive relationship between training and employee involvement on one hand and product and process innovation on the other hand.

Other studies have examined the HRM and innovation link for specific types of firms. For instance, a study conducted on UK manufacturing firms by Shipton et al. (2006) found that HR practices designed to enhance employee exploratory learning (e.g. employee engagement with parties external to their organization, intra-organizational secondment and on-the-job development) and HR practices intended to promote the exploitation of existing knowledge (e.g. training, appraisal, induction, and team working) significantly impact organizational innovation in terms of product innovation, and innovations in production technologies and procedures. According to the authors, exploratory-learning-enhancing HR practices amplify their positive effect on organizational innovation when used in conjunction with training, appraisal, induction, or team working. The authors also noted that although a contingent reward system has no direct impact on organizational innovation, its significant impact becomes apparent when used in conjunction with exploratory-learning-enhancing HR practices. In their study of Korean manufacturing firms, Sung and Choi (2018) argued that an HRM system including corporate training, external education, on-the-job training and task rotation exposes employees to new information and skills which subsequently expands and strengthens the unique knowledge stock of the firm for innovation. They further argued that a group-based and firm-based reward system encourages both vertical and horizontal flow of knowledge by aligning individual and/or group interest with the collective goal of the organisation. Their results indicate only knowledge flow mediates a positive relationship between HRM systems and innovation. Nonetheless, the authors found evidence indicating that innovation strategy moderates a positive relationship between knowledge stock and innovation. Similarly, Laursen and Foss's (2003) survey study on 1,900 Danish manufacturing firms found that seven out of nine HRM practices, including training, led to superior innovation performance. Chang et al. (2013) on the other hand found evidence to indicate that absorptive capacity mediates a positive relationship between innovation among Chinese high technology manufacturing firms and an HRM system which includes various forms of training, performance assessment processes, information sharing, and group-based and organisation-based pay. Collins and Smith (2006) considered knowledge-intensive firms in the US and identified selection, training and development, and compensation pay as a commitment-based HR system which creates organizational social climates such as trust, cooperation, and shared codes and language, which in turn facilitates employee knowledge exchange and combination, which subsequently impacts sales revenue from new products and services. Meanwhile, the study by Verburg et al. (2007) on Dutch human resource professionals concluded that an HR system which includes flexibility and professionalism influences managers' perceived organizational innovation relating to technological innovation and administrative innovation. De Winne and Sels (2010) examined the relationship between HRM and innovation in Belgian start-ups and highlighted the importance of HRM in promoting product and process innovation in participating firms. Meanwhile, Hailey's (2001) longitudinal case study on the head office of a UK-based multinational company found that training, appraisal system and performance management influence the organization's ability to innovate. Meanwhile, McGuirk et al. (2015) conceptualised innovative human capital as encompassing education, training, willingness to change in the workplace and job satisfaction, and show that both training participation and willingness to change on the part of employee-managers were significant predictors of innovation in small firms. Meanwhile both innovation capability and competitive advantage provide a mediation role between HRM practices including training, recruitment and selections, and innovation among Thailand SME's (Wongsansukcharoen and Thaweepaiboonwong, 2023).

4.3 Theoretical background and hypotheses development

HRM researchers have over the past couple of decades explored the relationship between HRM and organisational performance outcomes. Indeed, many researchers see understanding the mechanisms underlying this relationship as one of the essential objectives of strategic HRM research (e.g., Jiang et al., 2012; Patel et al., 2013). This stream of research has linked HRM to different categories of outcomes including employee-level outcomes such as employee skills and abilities, employee motivation, employee participation, and organisational-level outcomes such as productivity, product and service quality, dynamic capability, and innovation (Dyer and Reeves, 1995; Jiang Lepak et al., 2012; Zhou et al., 2022; Sheehan et al., 2023). It has also provided empirical evidence to suggest the employee-level outcomes mediate the relationship between HR practices and the organisational-level outcomes (e.g., Dyer and Reeves, 1995; Jiang et al., 2012).

Theoretically, the link between HRM and organizational performance has often been studied either by using the human capital and resource-based perspective, whereby HRM contributes to the competencies within the organisation, or using the behavioural perspective, whereby HRM impacts performance by influencing and aligning employees' attitudes and behaviours, or by the AMO framework (e.g., Schuler and Jackson, 1987; Coff and Kryscynski, 2011; Delery and Roumpi, 2017; Lee et al., 2019). On one hand, the human capital and resource-based perspective, which has received a significant amount of attention in the strategic management literature (Wernerfelt, 1984; Barney, 1991), focuses on how organizations can use competencies of their human capital resources (i.e., the knowledges, skills and abilities inherent in the people that make up the organisation) as a competitive asset and for higher performance. This suggests that human capital is a principal determinant of organisational performance when the return on investment in human capital exceeds the cost of investment in human capital (Lepak and Snell, 1999; Ployhart and Moliterno, 2011; Jiang, Lepak et al., 2013). The resource-based view of the firm also emphasises the need for organisations to integrate human resources into the design stage of their strategy, and it provides a framework for viewing and examining the potential for a given pool of human capital to execute a given strategy. This view argues that strategies are not universally executable, but are dependent on having the required human resource base to execute them (Grant, 1991). The resource-based theory further suggests that human capital resources can provide a sustained competitive advantage when they add positive value to the firm, constitute unique or rare skills among current and potential competitors, are not subject to replacement by technological advances, and are a representative of firms' investment that cannot be easily imitated (Barney, 1991; Wright and McMahan, 1992). Wright et al. (1994) theoretically outline the potential for human capital resources to constitute a source of sustained competitive advantage by demonstrating how they meet the criteria of valuability, rareness, inimitability and non-substitutability. First, human capital has the ability to create value when both demand for labour is heterogenous (i.e., firms have different jobs which require different competencies) and supply of labour is heterogenous (i.e., people differ in both the types and level of competencies). In this situation, there will be differentials in individual productivity contributions to the firm: thus, firms can create value through investment in human assets. Second, to the extent that all current and potential employees differ in both types and level of competencies which allow for differentials in individual contribution implies that human capital characteristics are normally distributed. Under such conditions, high quality human capital resources are rare. Thus, a firm could attract, obtain, and build individuals of superior competencies through a combination of valid selection programs, attractive reward systems, and training and development programs. Third, human capital resources, over time, are inimitable because they tend to be characterised by unique historical conditions (i.e., historical events that have shaped a firm's practices, policies and culture), causal ambiguity (i.e., competitors have imperfect understanding of how a firm's human capital acts as a competitive advantage), and social complexity (i.e., most social interactions are very complex making them impossible to be managed or influenced systematically). Wright and McMahan (1992) also argue that although the degree of imitability of a firm's human capital is low compared to equipment or facilities, investment in human capital, especially firm-specific human capital, decreases further the degree of imitability by providing a qualitative differentiation between its employees and those of its competitors. Finally, to the extent that constant training in state-of-the-art technological knowledge ensures that human resource does not become obsolete, and the fact that human abilities are transferable across a wide variety of technologies, products and markets, ensure that human capital resources are non-substitutable. Nonetheless, while human capital is important for HRM to impact performance, it is not sufficient. That is, the ability for human capital to impact performance is only possible to the extent that the focal individual is willing to permit the organisation to benefit.

Meanwhile, the behavioural perspective does not emphasise the knowledge, skills and abilities of individuals, but instead focuses only on how the organisation can elicit appropriate and productive role behaviours (e.g., motivation, commitment etc.) from its workforce. The rationale behind the behavioural model, as argued by Schuler and Jackson (1987), is based on what is needed from the workforce aside from the knowledge, technical skills and abilities required to execute a specific task. Wright et al. (1994) also argue that while individual must have the ability to exhibit the required behaviour necessary to impact performance, having the necessary ability does not guarantee that the require behaviour will be exhibited. The behavioural perspective has its roots in contingency theory (Fisher, 1989) and it is one of the original theoretical models used in the strategic human resource management (SHRM) literature to describe the relationship between HRM and performance. This perspective also suggests that organisations do not perform themselves, but instead use HR practices as enablers of productive role behaviour from the workforce to subsequently realise organisational outcomes. Thus, emphasising the mediating role of employees' behaviour between organizations' strategies and performance outcomes (Wright and McMahan, 1992). Taking a behavioural perspective, Schuler and Jackson (1987) adapted Porter's (1980) competitive strategies in discussing innovation. The authors emphasised the importance of employee role behaviour in the implementations of innovation strategies – innovation strategies require a high degree of innovative behaviour, a long-term focus, a high level of cooperative behaviour, a modest degree of concern for quality and quantity, and a greater degree of risk taking (Wright and McMahan, 1992).

Building on the behavioural approach and expectancy theory (Lawler, 1971), later strategic HRM scholars have drawn upon the AMO framework (Appelbaum et al., 2000) with the aim of providing a better synthesis of the mechanisms linking HRM practices and desired outcomes. This model proposes that the relationship between HRM practices and performance is mediated by three essential components: ability (A), motivation (M) and opportunity (O). Accordingly, an organisation is more likely to realise desirable strategic outcomes when its employees have the necessary knowledge, skills and abilities to make their efforts meaningful; employees are motivated to use their knowledge, skills and abilities; and the organisation provides employees with the opportunity to participate in substantive decisions through the way that work is organised. Extending this argument, HR systems designed to impact on organisational performance can be viewed as consisting of an appropriate combination of different HRM practices rather than individual practices that can ensure direct initial impact on human capital, employee motivation and opportunity to participate. In line with this logic, the current study conceptualised HR systems designed to maximise employee performance for innovation as consisting of three components intended to enhance human capital, and intended to enable motivation, and opportunities for human capital and motivation to be used. The mediating role of human capital, motivation and opportunity between HR systems and organisational performance is well established in the literature (e.g., Taggar, 2002; Amabile et al., 2002; West et al., 2004).

Analytically, researchers have examined the relationship between HRM and organisational performance by adopting either the best practice approach or the bundle/integrated approach (Boxall and Purcell, 2003; Delery and Doty, 1996; Comb et al., 2006; Delaney and Huselid, 1996). The assumption underlying the best practice approach is that organizations will improve their performance if they implement certain best HR practices (Wood, 1999). The bundle/integrated approach on the other hand emphasises the need to integrate the operation of bundles of individual HR practices in a complementary manner (Wood, 1999; Boxall and Macky, 2009; Boxall and Purcell, 2022). Some of these integrated HR practices have been labelled high-commitment work systems, high-involvement work systems or high-performance work systems. The general view is that HR practices contribute to firm performance through the application of both individual HR practices and bundles of HR practices (Lado and Wilson, 1994; Huselid, 1995). However, the literature suggests HR practices have a better effect on firm performance when they are adopted in a bundle rather than as individual components (Laursen and Foss, 2003; Laursen and Mahnke, 2001).

Connecting HR systems to innovation outcomes

Drawing on the behavioural perspective of HRM, human capital theory, and the resource-based view of the firm, this study delineates three components of HR systems, namely, human-capital-enhancing HR practices (HEH), motivation-enabling HR practices (MEH) and opportunity-enabling HR practices (OEH) and examines their respective influence on firm-level innovation.

Considering that the foundation of innovation is new ideas, and the fact that the acquisition, creation and transformation of new knowledge and ideas are inherently human processes (Van de Ven, 1986), implies that the success of innovation depends partly on human capital. Human capital is one of the most critical mediating factors between HRM and firm performance that has been examined in the literature (Gardner et al., 2011; Shaw et al., 2009; Batt and Colvin, 2011). Human capital theory and the resource-based view propose human capital as the principal determining factor of productivity (Dess and Shaw, 2001) and a source of competitive advantage (Wright et al., 1994).

Previous research has provided support for the positive effect of human capital on organisational performance including innovation (Crook et al., 2011). That is, organizations through their HR practices can acquire, develop and maintain valuable human capital, including both generic and organisation-specific human capital, which subsequently promotes high levels of knowledge recombination for innovation. Organizations' ability to innovate is dependent on the capabilities embedded in its human capital (Cohen and Levinthal, 1990) which commences by bringing talented people into the organization (Subramaniam and Youndt, 2005). First, recruitment procedures designed to seek out quality employees will have a substantial influence on the skills and capabilities new employees possess. For instance, a careful screening prior to selection enables organizations to identify valuable individuals in respect of their intrinsic motivation, task expertise, and cognitive skills (Jiang, Wang et al., 2012) and to expand the quality of their existing human capital base for effective exploration and exploitation of knowledge. Additionality, a comprehensive recruitment and selection process that systematically seeks out the best talent will allow the organization to draw the most talented people from a large pool of candidates to increase the overall human capital talent base needed to facilitate innovation. Similarly, staffing procedures that emphasise individual creative skills and communication abilities, and innovative approaches, promote innovation (Lee et al., 2019). Second, often included in the discussion of the determinants of human capital is training (Huselid, 1995; Pfeffer, 1998). Investment in employee development through training can facilitate learning in the organization, and can generate enhanced employees' collective knowledge capacity (Cohen and Levinthal, 1990) and creativity related skills necessary to facilitate innovation. Competencies for developing novel and useful ideas can be both developed and enhanced in employees through training. Effective on-the-job or off-the-job training has the potential to enhance the knowledge, skills and abilities which employees can use as leverage for the firm's benefit (Blume et al., 2010). Stocks of high-quality human capital facilitate the absorption of superior technologies from the environment essential for the transformation of knowledge into innovation output. Similarly, training that seeks to develop and enhance employees' ability to generate novel ideas, transfer knowledge to others via effective communication and implement new ideas facilitates innovation proactivity behaviour among employees (Lee et al., 2019). Thus, organisations can use HR practices that focus on acquiring and developing skills, knowledge and abilities to create enhanced capabilities for innovation. In other words, organisations can enhance their human capital through either recruitment or training, permitting the hypothesis:

> *H1: Human-capital enhancing HR practices including quality employee identification processes and employee development through training will exert a positive effect on firm innovation.*

Although employees may possess the necessary competencies to implement organisational strategies, having the competencies does not guarantee that the required productive role behaviour will be exhibited by the employees. That is, a human capital pool is a necessary but not sufficient condition for human resources to impact on performance. The potential of human capital is feasible only to the extent to which individual employees who possess the human capital permit the organisation to benefit. The Social exchange theory (Blau,1964) and the reciprocity theory (Gouldner, 1960) also suggest that employees who perceive employer's actions toward them as beneficial may feel obliged to respond and be motivated to exert more effort at work. In view of this, an organisation having obtained a high-quality human capital pool needs to develop HR practices that enhance the intrinsic and extrinsic motivation of employee to use their capabilities to support organisational strategies (Jackson and Schuler, 1995). More specifically, motivation-enabling HR practices such as competitive reward systems have been found not only to attract high-quality individuals into the organisation, but also have the potential to provide existing employees with extrinsic motivation that connects their work efforts to external rewards (Jiang, Wang et al., 2012). This might relate to fairness within the organisation so the people perceive the organisation as being fair, in that people who work more effectively are paid more. Similarly, performance evaluations and post-training assessment procedures that seek to promote employees' learning, development and growth help to generate employees' intrinsic motivation, which encourages them seek out higher learning opportunities (Stiles et al., 1997), which in turn can enhance their knowledge capability for innovative purposes. Furthermore, feedback from performance evaluations lead to the recognition of gaps between performance and targets (Guzzo et al., 1985). This can motivate people to seek bridging the gaps by for instance taking up training or mentorship within the organisation, or even undertaking further education outside the organization. Furthermore, the recognition of gaps might motivate people to seek innovative ways of doing work. The motivating merits of employee performance review is particularly enhanced if the evaluation or assessment process tolerates errors (Wang et al., 2020) in situations where the employee follows work procedures – this can encourage people to experiment with new ideas having the assurance that they will not be penalised for errors as long as they adhere to work procedures in their quest to improve performance. Thus, error tolerance might encourage mastery experience which can consequently boost one's self-efficacy; and one's quest to improve performance might lead to spillovers in the person's innovation performance. In summary, HR practices can enable motivation within organisation, which is essential for the workforce to use their competencies to achieve innovation – leading to the hypothesis that:

> *H2: Motivation-enabling HR practices including employee performance reviews and rewards will exert a positive effect on firm innovation.*

Turning to the opportunity aspect of the AMO model, an organization may be endowed with high-quality human capital with the potential and motivation to create and transform knowledge for organisational outcomes. However, such potential may not be realised without appropriate organisational structures that support employees to use their human capital to contribute to organisational goals. Moreover, researchers taking the human capital and resource-based perspective suggest that the value of employees' human capital can be realised if organisations use HR practices that enhance the opportunities for employees use their competencies. The central argument of the opportunity aspect of the AMO model concerns how work is organised. For instance, keeping talented employees in a more knowledge stimulating environment enables the development and calibration of more advanced knowledge (Wernerfelt, 1984) for high organisation performance. Specifically, job designs that encourage employees' sense of autonomy, enable them apply their experience, knowledge and skills to experiment with new ideas, create new ideas and solve problems. Allowing employees to make discretionary decisions concerning their task gives them the opportunity to experiment with new ideas that may in turn lead to the attainment of organizational outcomes. Creating an organizational culture that facilitates employee co-operation and knowledge sharing through teamwork has been found to be crucial for knowledge exploration, ideas generation and recombination for high organisational performance (Collins and Smith, 2005). According to Pfeffer (1998), team-based organizations will have all their employees feeling responsible and accountable for the success of the organization. This increased sense of accountability and responsibility stimulates more initiative and innovativeness among all employees involved. Similarly, organizing employees into teams to work on projects provides them with a variety of knowledge bases and an opportunity to share ideas and contribute to new knowledge creation, thus enabling their human capital to be harnessed. Working in teams enables the creation of new knowledge by connecting otherwise previously separated ideas and knowledge, or by recombining previously connected ideas and knowledge in novel ways (Kogut and Zander, 1992; Nahapiet and Ghoshal, 1998). Project team working also offers employees more opportunities to communicate and cooperate with each other and to exchange information and new ideas, and also provides a framework in which members are keener to help one another and freely share their knowledge. Members can then build on others' ideas for innovation aspirations, especially if members are trained in effective team processes and problem solving. Team working facilitates knowledge transfer among team members and provides opportunities for mutual learning, which subsequently stimulates the creation of new knowledge and contributes to organizations' ability to innovate (Tsai, 2001), hence the hypothesis:

> *H3: Opportunity enabling HR practices including team working, task discretion, task variety and flexible working will promote innovation.*

4.4 Methodology

4.4.1 Data

We tested our hypotheses by combining the UK Innovation Survey (UKIS) dataset with that from the UK Employer Skills Survey (ESS)[6]. The UKIS is an official survey conducted every two years by the Office for National Statistics on behalf of the Department of Business Innovation and Skills (BIS), and it is part of the European Union Community Innovation Survey (CIS). We use data from UKIS 2015, UKIS 2017 and UKIS 2019, respectively covering the periods 2012-2014, 2014-2016 and 2016-2018. All the control variables as well as the innovation measures were taken from the innovation survey (UKIS) while the HRM practice measures were taken from the skills survey (ESS). The merging process was done in such a way that each of the three innovation surveys was merged with a corresponding ESS that was undertaken 2 years prior to the innovation survey period. The implication of this is that the HR practice would have been implemented by the firm at least 1 year and at most 3 years prior to

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[6] The Employer Skill Survey, ESS 2011 (ESS 2013 and ESS 2015) sampled 87,572 (91,279 and 91,210) UK enterprises and obtained a response rate of 39% (44% and 42%)

innovation. Observations from the UKIS were matched with that of the ESS at the enterprise level. We specifically merged UKIS (2012-2014) with ESS (2011); UKIS (2014-2016) with ESS (2013); UKIS (2016-2018) with ESS (2015). The lags implicit in the merging process give us the opportunity infer causal effects of HRM on firm innovation in the event of a significant relationship.

4.4.2 Measures

Innovation propensity

While very limited empirical attention has been paid to the HRM and innovation link, the few studies that have taken such consideration often use perceptual measures to gauge firm innovation performance (e.g., Ahmad and Schroeder, 2003), instead of the generally preferred objective measures such as the ones employed in this study. We specifically measure firm innovation performance by three objective measures, namely, product innovation, process innovation and organization innovation. These measures are binary indicators and are represented in the UKIS as the introduction of new or significantly improved products (goods or services), the introduction of new or significantly improved methods for the production or supply of goods or services, and the introduction of new or significantly improved business strategy or practice. We thus measure product innovation by a binary variable taking value one if the firm introduced product innovation during the three years of survey period and zero otherwise. Similarly, process innovation is measured by a binary indicator representing one if the firm introduced process innovation during the three years of the survey period and zero otherwise.

Organization innovation is a binary indicator that is constructed from four survey questions relating to innovation in business strategies and practices that seeks to increase the firm's internal efficiency or the effectiveness of approaching markets and customers. These questions asked whether during the survey period the firm: introduced new business practices for organising procedures (e.g., knowledge management, lean production, business re-engineering), introduced new methods of organising work responsibilities (e.g., teamwork, decentralisation, education / training systems), introduced new methods of organising external relationships with other firms and public institutions, or implemented major changes in marketing concepts or strategies. We assume the four metrics listed above are all manifestations of the underlying idea of organization innovation, and thence combine them together. Our organization innovation indicator is subsequently represented as one if firms answered yes to any of the four questions and zero if firm answered no to all four questions. All our three innovation indicators represent the propensity to innovate. Using different innovation variables allows testing whether different HRM systems have differing effects on the propensity of innovation in goods or services, processes for the production or supply of goods or services, and organizational practices or strategies.

HR systems

The HR practices used were based on examples of HR practices shown in previous studies to be supportive of innovation. Based on 12 HRM practices identified in the ESS, we constructed three components of HR systems, namely, Human-capital Enhancing HR (HEH) system, Motivation Enabling HR (MEH) system, and Opportunity Enabling HR (OEH) system.

The Human-capital Enhancing HR (HEH) system consists of HR practices that relate to the staffing of the organization and employee development through training. HR practices in this system includes on or off the job training and the use of quality employee identification processes. The central argument here is that organizations can enhance human capital though either training or quality employee identification processes. The HEH system variable is therefore measured by a binary indicator represented by one if the firm reported as having any of these two HR practices and zero otherwise. The Motivation Enabling HR (MEH) system includes practices such as personal pay and bonuses, flexible benefits, performance reviews, and post-training assessment. The variable MEH is thus measured by a binary indicator represented by one if the firm reported as having any of these four HR practices and zero otherwise. Again, the argument here is that each of the HR practices in the MEH construct can enable motivation. The final HR system, the Opportunity Enabling HR (OEH) system consists of HR practices that entails the design and organization of work in the firms. These include, putting employees in teams to work on projects, task variety, task discretion and flexible working. Like the other system variables, the OEH variable is measured by a binary variable indicating one if the firm reported as having any of the four HR practices in the construct.

Control variables

To estimate the possible causal effect of HRM systems on firm innovation, we control for other firm-level characteristics that have been found in the innovation literature to exert influence on the innovativeness of firms. For instance, we control for internal R&D and investment in innovation training with two dummies to account for the innovative capability of the firm. We also include the firms' external collaboration links to control for the potential effect of external knowledge spillovers (Laursen and Salter, 2006; Roper, Love and Bonner, 2017; Roper and Love, 2018), and collaboration squared to account for possible non-linear effect of collaboration on innovation. Included also as a control is an export dummy which may reveal a firm's competitiveness in the international markets, possibly characterized by higher productivity levels with higher potential for innovations (Bernard and Jensen, 1999). We also control for firm size measured by employment (logged) as firms with large operating scale are likely to have the slack resources and managerial capability to implement HR and to launch innovation (Shin and Konrad, 2017), employment squared (logged). Also included as controls are the extent of firms' skills base, and dummies for science-degree and other-degree to account for the extent of human resource capability embedded in the firm. Finally, we include industry dummies to account for possible industry effects.

Reported in Table 4.1 are the means, standard deviations and correlations of the variables used in our analysis. Out of a total sample of 2,450, about 22%, 17% and 30% were respectively product innovators, process innovators, and organization innovators. About 20% of firms undertook internal R&D and 30% are exporters, and firms on average engaged in two external collaboration linkages. Similarly, out of 1,230 observations, about 73%, 88% and 91% respectively reported having OEH, staffing and development system and performance and reward system. The correlations among the three innovation measures are not very strong suggesting innovators in our sample are slightly different in terms of product, process and organization innovation. Similar low corrections are observed among the three components of HRM systems

Reported also in Table 4.2 is the distribution of the innovation variables and HR system variables across firm sizes and industry. We observe that regardless of firms' size or industry, a greater proportion of the firms engaged in organization innovation, followed by product innovation and then process innovation. For instance, out of 1,012 small firms, 34.2%, 22.7% and 17.1% engaged respectively in organization innovation, product innovation and process innovation. On the other hand, while a similar proportion of manufacturing firms engaged in product, process or organization innovation (i.e., about 30%), the majority of the service firms engaged in organization innovation (i.e., about 36%) with few of them engaging in process innovation (17%). The descriptive statistics indicates that a higher proportion of medium-large firms adopt the use of HRM practices than their small firm counterparts.

Table 4.1: Mean, standard deviation, and correlation matrix for variables used in analysis

	Variable	OBS	Mean	STD	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Product innovation (0/1)	2450	0.22	0.41													
2	Process innovation (0/1)	2450	0.17	0.37	0.46												
3	Organization Innovation (0/1)	2450	0.30	0.46	0.32	0.29											
4	Human-capital-enhancing system (0/1)	1230	0.88	0.32	0.07	0.07	0.09										
5	Motivation-enabling system (0/1)	1230	0.91	0.29	0.05	0.05	0.05	0.26									
6	Opportunity-enabling system (0/1)	1230	0.73	0.44	0.07	0.04	0.06	0.11	0.08								
7	Internal R&D (0/1)	2450	0.20	0.40	0.50	0.39	0.29	0.01	0.05	0.04							
8	Collaboration (1-10)	2450	2.26	3.42	0.44	0.34	0.25	0.03	0.05	0.05	0.46						
9	Innovation training 0/1)	2450	0.15	0.36	0.37	0.33	0.37	0.01	0.09	0.06	0.34	0.34					
10	Skill base (0-6)	2450	1.14	1.62	0.33	0.22	0.18	0.03	0.05	0.07	0.37	0.41	0.24				
11	Export (0/1)	2450	0.26	0.44	0.24	0.15	0.14	-0.03	0.09	0.06	0.31	0.23	0.12	0.27			
12	Science degree (0/1)	2450	0.31	0.46	0.23	0.18	0.12	0.07	0.13	0.07	0.31	0.34	0.20	0.42	0.26		
13	Other degree (0/1)	2450	0.46	0.50	0.17	0.12	0.10	0.01	0.07	0.07	0.21	0.30	0.13	0.39	0.19	0.50	
14	Employment (logged)	2450	4.44	1.59	-0.02	-0.02	-0.08	0.09	0.13	0.18	0.02	0.15	-0.04	0.19	0.01	0.12	0.09

Note: Dichotomous sector dummies are not listed in the table

Table 4.2: Descriptive statistics of main variables across size and industry

	Manufacturing			Service			Small (10-50 employment)			Medium-large (50+ employees)		
Variable	OBS	Mean	STD	OBS	Mean	STD	OBS	Mean	STD	OBS	Mean	STD
Product innovation	412	0.30	0.46	1817	0.20	0.40	1012	0.23	0.42	1438	0.21	0.41
Process innovation	412	0.25	0.44	1817	0.15	0.36	1012	0.17	0.38	1438	0.17	0.37
Organization innovation	412	0.31	0.46	1817	0.36	0.46	1012	0.34	0.48	1438	0.27	0.44
Human-capital-enhancing system	217	0.87	0.34	901	0.89	0.32	493	0.84	0.37	737	0.92	0.28
Motivation-enabling system	217	0.89	0.32	901	0.92	0.27	493	0.86	0.35	737	0.94	0.23
Opportunity-enabling system	217	0.70	0.46	901	0.74	0.44	493	0.69	0.46	737	0.76	0.43

4.5 Empirical results and discussion

Reported in Table 4.3 are the logit regression estimation results for the three innovation models across the three HR components. In consensus with the literature, internal R&D, the extent of collaboration with external institutions and innovation training are positive, and significantly determine firms' propensity to innovate. The skills base variable on the other hand seems to be relevant for only product innovation as we observe a significantly positive coefficient for the product innovation model across all the three HR components. Our models have a very good fit as we report between 79.92% and 86.91% correctly specified observations based on the logit regression models.

As already explained in section 4.4.1 the HR variables lag the innovation variables as well as the control variables by a period of 1-3 years allowing us to cautiously interpret the coefficient estimates associated with the HR components as causal effects on firms' propensity to innovate. The results as per Table 4.3 indicate that ***human-capital enhancing HR practices (HEH)*** including on-or-off the job training and quality employee identification processes at the 5% significance level determine the propensity to introduce process innovation (b=0.822) and at the 1% level determines organization innovation (b=0.995). ***Motivation enabling HR practices (MEH)*** including performance reviews and rewards significantly determine firms' propensity to introduce process innovation (b=1.036 at 5% level). Although their measure of innovation and HR practices were based on managerial subjective perception, Andreeva et al.'s (2017) study on Finnish companies found a similar result regarding a positive relationship between the joint use performance appraisal and reward on one hand and incremental innovation on the other hand. Meanwhile, ***Opportunity enabling HR practices (OEH)*** including flexible working, working on projects in teams, task variety, and task discretion at the 10% significance level determine the propensity for product innovation (b=0.649) and at the 1% significance level determine the propensity for organizational innovation (b=0.651). The positive results we found for our OEH and HEH dimensions broadly confirm the results of Li et al.'s (2018) study which indicates HR practices (which they termed "high-involving work system") including flexible job design, training and teamwork significantly increase the propensity to introduce either or both product and process innovation in Canadian firms.

Column 2-4 of Table 4.4 reports the marginal effect estimation results from the logit regression relating to the three innovation models across the three HR components for the full sample. The estimated results for the full sample analysis indicate that on average, the use of ***human-***

capital enhancing HR (HEH) practices including training and quality employee identification processes increase the chances of process and organization innovation in participating firms: About 9% increase in the case of process innovation and about 13% increase in the case of organization innovation, respectively at the 5% and 0.1% significant level. This suggests that obtaining valuable employees and enhancing employees' skills, knowledge and ability contribute to internal organisational capabilities associated with innovation (Gahan et al., 2021). This result is in line with that of previous studies in the literature indicating a significant positive impact of training on employees' exploratory learning and creativity, and subsequent positive impact on innovation (Shipton et al., 2006; Beugelsdijk, 2008; Jiang, Wang et al., 2012). Other studies have found quality employee identification processes (e.g., recruitment and selection) and training to exert positive impacts on firms' human capital and subsequently impact firm innovation and productivity (Jiang, Lepak et al., 2012; Chang et al., 2013)

Similarly, the adoption of ***motivation-enabling HR (MOH)*** practices which includes performance review and rewards are found to increase the likelihood of process innovation among participating firms by about 12% points. This is in consensus with the findings of a previous study which indicates that rewards facilitate employee creativity for administrative, product and process innovations (Jiang, Wang et al., 2012). Although performance appraisal has been found by a prior study to have a negative effect on employee creativity (Jiang, Wang et al., 2012), our result confirms the general consensus in the literature indicating a positive effect of performance appraisal on both product and process innovation (Hailey, 2001; Shipton et al., 2006; Chang and Huang, 2008; Jimenez-Jimenez and Sanz-Valle, 2008). Chang et al. (2013) also found performance assessment processes, organization-based and group-based pay systems impact innovation in Chinese high-tech firms through their impact on absorptive capacity. Similar results were reported by Jiang, Lepak et al. (2012) suggesting employees' motivation mediates a positive relationship between performance appraisal, compensation, incentives and benefits on one side and operational outcomes such as innovation, productivity and quality on the other side.

It is also noteworthy that there are lots of overlaps between the human-capital enhancing practices and the motivation-enabling practices. For instance, while reward can be seen as a motivating HR practice, there is another aspect of reward where economics scholars argue for its capacity to enhance human capital by attracting high quality individuals into the organization.

Finally, ***opportunity-enabling HR (OEH)*** practices lead to about 6% increase in propensity to introduce new or significantly improve products and about 9% increase in propensity to introduce organization innovation, respectively at the 5% and 1% significant levels, broadly confirming the result of Jiang, Wang et al.'s (2012) study which indicates job designs and teamwork significantly impact firms' product, process and administrative innovation. A meta-analysis study by Jiang, Lepak et al. (2012) also found HR practices including job designs and teamwork enhance the opportunity for employees to contribute their competencies to innovation and other operational outcomes such as productivity and product quality.

Table 4.3: Logit regression results - Full sample

	Product innovation	Process innovation	Organization innovation	Product innovation	Process innovation	Organization innovation	Product innovation	Process innovation	Organization innovation
Internal R&D	1.985***	1.408***	1.229***	1.979***	1.422***	1.209***	2.013***	1.416***	1.238***
	(0.337)	(0.297)	(0.296)	(0.333)	(0.290)	(0.294)	(0.331)	(0.295)	(0.297)
Collaboration	1.273***	0.513*	1.789***	1.281***	0.526*	1.773***	1.296***	0.512*	1.793***
	(0.230)	(0.226)	(0.286)	(0.228)	(0.226)	(0.281)	(0.224)	(0.220)	(0.289)
Collaboration²	-0.133***	-0.046	-0.207***	-0.134***	-0.048	-0.205***	-0.136***	-0.046	-0.208***
	(0.028)	(0.027)	(0.036)	(0.028)	(0.027)	(0.035)	(0.028)	(0.026)	(0.036)
Innovation training	1.324***	1.395***	1.299***	1.344***	1.409***	1.320***	1.365***	1.427***	1.335***
	(0.334)	(0.304)	(0.296)	(0.332)	(0.301)	(0.295)	(0.337)	(0.302)	(0.298)
Skills base	0.198*	0.0961	-0.101	0.196*	0.102	-0.114	0.210*	0.101	-0.105
	(0.089)	(0.074)	(0.076)	(0.088)	(0.073)	(0.073)	(0.087)	(0.072)	(0.074)
Export	0.0589	0.0962	0.2900	0.0849	0.0862	0.348	0.176	0.162	0.416
	(0.375)	(0.301)	(0.276)	(0.370)	(0.303)	(0.267)	(0.377)	(0.297)	(0.273)
Degree (science)	0.186	0.292	-0.497	0.208	0.322	-0.415	0.1120	0.2800	-0.474
	(0.332)	(0.287)	(0.262)	(0.329)	(0.288)	(0.259)	(0.337)	(0.289)	(0.261)
Degree (other)	-0.171	-0.0649	0.0105	-0.174	-0.0522	0.0246	-0.176	-0.0388	0.0393
	(0.317)	(0.280)	(0.228)	(0.314)	(0.281)	(0.224)	(0.315)	(0.280)	(0.225)
Employment (logged)	0.0122	-0.0332	-0.151*	0.0112	-0.044	-0.138*	-0.00237	-0.0318	-0.161*
	(0.106)	(0.085)	(0.065)	(0.107)	(0.087)	(0.065	(0.110)	(0.087)	(0.065)
HEH system	0.458	**0.822***	**0.995****						
	(0.414)	**(0.403)**	**(0.308)**						
MEH system				0.35	**1.036***	0.221			
				(0.557)	**(0.493)**	(0.284)			
OEH system							**0.649**⁺	0.467	**0.651****
							(0.334)	(0.299)	**(0.228)**
Constant	-3.335**	-2.777***	-1.06	-3.250**	-2.973***	-0.35	-3.393***	-2.619**	-0.0509
	(1.070)	(0.785)	(1.210)	(1.127)	(0.784)	(1.202)	(1.029)	(0.802)	(1.170)
Observations	833	748	951	833	748	951	833	748	951
Pseudo R²	0.46	0.31	0.29	0.46	0.31	0.28	0.46	0.31	0.29
Log- likelihood	-257.72	-282.41	-426.47	-258.067	-282.17	-431.10	-256.04	-282.93	-426.85
Correct predictions (%)	86.8	83.3	80.0	86.7	84.5	80.0	86.9	83.8	81.1

Notes: Robust standard errors are in parentheses. ***, **, * and ⁺ signify 0.1%, 1%, 5% and 10% significance levels.
Four-digit NACE industry dummies included.

Table 4.4: Marginal effect of HRM system on firms' innovation performance - Full sample and across industry

	Full sample			Manufacturing			Service		
	Product innovation	Process innovation	Organization innovation	Product innovation	Process innovation	Organization innovation	Product innovation	Process innovation	Organization innovation
Human-capital enhancing system	0.041	**0.088***	**0.128*****	0.081	0.116	**0.166** $^{+}$	0.026	0.015	**0.086***
	(0.035)	(0.039)	(0.035)	(0.065)	(0.103)	(0.089)	(0.036)	(0.034)	(0.042)
Motivation-enabling System	0.033	**0.122***	0.0322	0.018	-0.027	0.118	0.014	0.050	0.032)
	(0.052)	(0.058)	(0.042)	(0.061)	(0.071)	(0.106)	(0.044)	(0.047	(0.048)
Opportunity-enabling System	**0.058***	0.053	**0.090****	0.045	-0.008	**0.148***	**0.061***	**0.052**$^{+}$	0.046
	(0.029)	(0.033)	(0.030)	(0.053)	(0.056)	(0.070)	(0.028)	(0.027	(0.030)

Notes: Robust standard errors are in parentheses. ***, **, * and $^{+}$ signify 0.1%, 1%, 5% and 10% significance levels

Table 4.5: Marginal effect of HRM system on firms' innovation performance - across sizeband

	Small (10-49 employment)			Medium-large (50+ employment)		
	Product innovation	Process innovation	Organization innovation	Product innovation	Process innovation	Organization innovation
Human-capital enhancing system	0.055 (0.068)	0.031 (0.087)	**0.172*** (0.074)	0.036 (0.061)	**0.120^{+}** (0.068)	**0.135^{+}** (0.069)
Motivation-enabling system	0.091 (0.127)	0.013 (0.152)	0.008 (0.076)	0.032 (0.075)	**0.171*** (0.079)	0.056 (0.076)
Opportunity - enabling system	0.084 (0.057)	**0.163*** (0.073)	**0.174**** (0.067)	**0.095^{+}** (0.049)	-0.012 (0.053)	0.070 (0.047)

Notes: Robust standard errors are in parentheses. ***, **, * and $^{+}$ signify 0.1%, 1%, 5% and 10% significance levels.

Reported in Column 5-10 of Table 4.4 is the marginal effect estimation of the effects of HRM for manufacturing and services firms. The results indicate that, for manufacturing businesses, HR systems promote only organisation innovation, with 16.3% and 14.8% organisation innovation effect respectively for the adoption of human-capital-enabling system and opportunity-enabling system. This result seems to suggest that HR system matter only for organisation innovation in manufacturing businesses. This may highlight the fact that unlike service firms which often rely on the workforce to improve processes of service delivery, manufacturing firms typically rely on various industrial engineering techniques to improve processes and practices for product innovation through a routinized and uninterrupted system. That is, in an effort to reduce or eliminate environmental uncertainties and thence maximize innovative productivity, manufacturing firms, particularly large manufacturing firms operate a hierarchically-managed system where managers define workers activities (Stinchcombe, 2000). In terms of service firms, human-capital-enabling system impact only organisation innovation, with participation leading to an 8.6 percentage points more likelihood of innovation. Also, among service firms, the adoption of opportunity-enabling system promotes both product and process innovation respectively at 6.1% and 5.2%. Service firms differ in the nature of knowledge, jurisdiction of control and the nature of client relationships, which in turn impact on heterogeneity in how the individual firms are organised (Malhotra et al., 2006; Malhotra and Morris, 2009). Moreover, the labour-intensive nature of many service firms implies that there is a high degree of reliance on the interpretation and judgment of the firm's workforce during product and service delivery (Robertson et al., 2003). These emphasize the latter part of our results regarding the need for service firms to empower their workforce to leverage their skills, knowledge and abilities to create greater innovation advantage.

Finally, we report the marginal effect estimation result of innovation effect of HR systems across firm sizes in Table 4.5. Overall, small firms respond well to opportunity-enabling HR system compared to medium-small firms. Specifically, opportunity-enabling HR system impact both process and organisation innovation in small business respectively at the 16.3% and 17.4%, compared to its impact on only product innovation in medium-large business, participating medium-large firms experiencing only 9.5% effect. This result seems to suggest that opportunity-enabling HR system is more beneficial for firms that may be lower in terms of capital resource intensity. Relatively, medium-large firms are more capital-intensive than small firms, while small firms are often labour-intensive than medium-large firms (Chadwick et al., 2013; Wu et al., 2015). An argument in the strategic human resource management literature indicates that human resource impact has an inverse relationship with the capital intensity within a business. Similarly, most decisions in small firms are done informally and the organisation of processes might also be informal. For instance, there are industrial engineering techniques that one would expect the likelihood of adoption to be far greater among large firms relative to small firms, which implies that opportunity-enabling system impact on innovation in small firms more than in large firms. Thus, opportunity-enabling HR system which is design to empower the firm's workforce to leverage their skills, knowledge and ability should offer greater innovation advantage in labour intensive businesses than in capital intensive businesses. We also observe that the product innovation impact of both human-capital-enabling system and motivation-enabling system is larger in small firms than in medium-large firms, albeit insignificant in both cases. This typically shows that the product innovation impact of HR systems is inconsistent among firms due to high inter-firm variations, particularly in small firms. While small firms are on a whole less well-managed, some are well-managed, meaning that the high form of results heterogeneity found among small firms are quite as expected (Federico and Capelleras, 2015). Inconsistency in results may also mean that there are some elements of complementarity that need to be accounted for: In addition to HR system, other firm-specific resources greatly shape the manner in which firms organise their innovation activities, and the subsequent technological performance they can realise, suggesting that HRM systems should be accompanied by other resources to be able to enhance innovation productivity.

So far, the result for this current study show heterogeneity in the relationship between HRM systems and innovation. Specifically, while some HRM systems impact some aspects of innovation, they do not for other types of innovation, suggesting that the relationship between

HRM systems and innovation may be influenced by inter-firm heterogeneity (Srholec and Verspagen, 2012; Federico and Capelleras, 2015). The strategic management literature provides insight into how key within-firm characteristics shape performance outcomes. According to the resource-based literature, within-firm attributes, possessions, and actions are key driving force behind the emergence of differences in between-firm performance (Short et al., 2007; Noda and Collis, 2001). This implies that individual firm-level choices, resources and capabilities and the implications for their performances could be still different even within the same industry or dimensions of firm size. For instance, there are industry-level analyses which suggest that firm-specific attributes contribute significantly to the explanation of differential in relationship between causes and effects than industry-specific characteristics (Goddard et al., 2009; Short et al., 2007). Goddard et al. (2009) empirically show that organisational structures and management practices at the firm-level represent a major source of variation in performance between firms in the same industry. Similarly, Short et al. (2007) argue that firm-specific characteristics generally offer the greatest explanatory power compared to industry features in explaining between-firm performance variances. The implications for the AMO framework are discussed in the conclusion following this section.

Table 4.6: Symbolic representation of innovation impact of HRM research

HRM Systems	Product innovation	Process innovation	Organization innovation
Full sample result			
Human-capital enhancing practices	(+)	+	+
Motivation enabling practices	(+)	+	(+)
Opportunity enabling practices	+	(+)	+
Manufacturing			
Human-capital enhancing practices	(+)	(+)	+
Motivation enabling practices	(+)	(-)	(+)
Opportunity enabling practices	(+)	(-)	+
Service			
Human-capital enhancing practices	(+)	(+)	+
Motivation enabling practices	(+)	(+)	(+)
Opportunity enabling practices	+	+	(+)
Small			
Human-capital enhancing practices	(+)	(+)	+
Motivation enabling practices	(+)	(+)	(+)
Opportunity enabling practices	(+)	+	+
Medium-large			
Human-capital enhancing practices	(+)	+	+
Motivation enabling practices	(+)	+	(+)
Opportunity enabling practices	+	(-)	(+)

Notes: + Means significant positive effect.
(+) Means insignificant positive.
(-) Means insignificant negative.

4.6 Conclusion

Our study attempts to uncover an antecedent of firm innovation by investigating how human resource management impacts firm-level innovation. Based on the behavioural perspective of HRM, human capital theory, the resource-based view of the firm and the system approach to HRM, this study revealed three components of HR systems, namely, human-capital enhancing HR (HEH) practices, motivation enabling HR (MEH) practices and opportunity enabling HR (OEH) practices which facilitate firm-level innovation. Three innovation outcomes are considered, namely, product innovation, process innovation, and organization innovation. Results indicate that the benefits of alternative forms of HR is contingent on the kind of innovation.

Table 4.6 presents the symbolic summary of all coefficients estimated in the current analysis (see Tables 4.3 – 4.5 for the actual coefficient estimates and their respective significance level). The empirical results indicate that the HEH system significantly promotes both process and organization innovation. The effect of HEH system on product innovation is positive although insignificant. We thus find support for our H1 regarding process and organization innovation but not for product innovation. H1 states "*Human-capital enhancing HR practices including quality employee identification processes and employee development through training will exert a positive effect on firm innovation.*"

In terms of H2, which states "*Motivation enabling HR practices including employee performance reviews and rewards will exert a positive effect on firm innovation",* there is confirmation for only process innovation as we observe a significant effect of the MEH system on the propensity to introduce process innovation. No confirmation is found for H2 in respects of product and organization innovation; the estimated coefficients are insignificant albeit positive.

Finally, the OEH system (which includes flexible working, working on projects in teams, task variety, and task discretion) significantly impacts the propensity for both product and organization innovation. The effect of the OEH system on process innovation is also positive albeit insignificant. That is, we find confirmation for H3 in terms of product innovation and organization innovation, but no confirmation in terms of process innovation. H3 states that "*Opportunity-enabling HR practices including team working, task discretion, task variety and flexible working will promote innovation.".*

Overall, the results indicate different emphasis of the AMO components for different innovation outcomes and for different types of firms. That is, different recipe from the AMO menu is emphasized depending on firm-specific context. Meanwhile, our descriptive analysis indicates weak correlations among the three innovation outcomes (between 0.29 and 0.46), implying that there are some firms that undertake individual innovations and such firms will need not all but some aspects of the AMO. There is also quite a sizeable set of firms who will be emphasizing two or three innovations, and for such firms all aspects of the AMO are important. Specifically, we find that opportunity-enabling system (i.e., the part of the AMO which concerns how firms organise work) seems to be the only aspect of the AMO that is needed for ***product innovation***. The implication of this is perhaps a slightly more democratic type of organization work is important for firms that are seeking product innovation. We will however caution readers not to disregard the need for top management to have a track record of bringing innovation forward; only that democratic organization seems to make a difference for product innovation according to our data. ***Organization innovation*** on the other hand requires both the opportunity-enabling and human-capital-enhancing aspects of the AMO. This means that while democratic organization is important for organization innovation, it might be easier to achieve with a greater level of human capital in the firm. Meanwhile, ***process innovation*** requires both human-capital-enhancing and motivation-enabling. Opportunity-enabling seems not to be important for process innovation. This is not surprising since process innovation is about routines and quite often about consistency. Allowing, for instance, task discretion (which is an opportunity-enabling HR practice) on an assembly line might be more harmful than good.

Firm heterogeneity across HRM effects

Surprisingly, HRM seems to promote only organization innovation in **manufacturing firms.** That is, we did not find significant results to suggest that any of the three HR components promoted product or process innovation in participating manufacturing firms. We however record positive (insignificant) estimates for all the three HR components in regards to product innovation, confirming the findings of Shipton et al.'s (2006) study of UK manufacturing firms which indicate that five out of six HRM practices, including team working, training, and appraisal are positively and significantly associated with product innovation when practices are adopted individually or as a system. On the other hand, the adoption of the OEH system or the HEH system significantly increases the likelihood of organization innovation respectively by about 15% and 17% points for manufacturing firms, compared to only about 9% points that service firms experience from the adoption of HEH system. These results broadly support Laursen and Foss's (2003) study of Danish firms with evidence indicating nine HRM practices adopted by firms, including training, resulted in high innovation performance with the impact being more marked for manufacturing than for service firms. Similar findings have previously been reported by Katou and Budhwar's (2006) in a study of Greek manufacturing firms and Lau and Ngo's (2004) survey study of 332 firms in Hong Kong.

Meanwhile, innovation in the ***service industry*** is significantly promoted by OEH and MEH systems albeit on a contingent basis. This is in line with the findings of Messersmith and Guthrie's (2010) study which indicates the adoption of high-performance work system

(HPWS) is associated with higher levels of product innovation and organization innovation in service firms. On another note, human-capital enhancing practices such as selection, training and development have been found to create a climate of trust and cooperation which facilitates knowledge exchange among employees for high product and service innovation performance among knowledge intensive service firms (Collins and Smith, 2006), while employees' innovative work behaviour mediates a positive link between HPWS which includes selection, training, compensation, and performance management and innovation in the form of revenue per employee generated from new clients and new services/products. The authors also established that the use of this HPWS has a significantly positive direct effect on innovation (Fu et al., 2015). Walsworth and Verm's (2007) study also found training to promote internationalisation for product and process innovation in high-tech manufacturing firms.

Similar to manufacturing firms, we did not find significant results to suggest that any of the three HR components promoted product innovation in participating ***small firms***. This finding may be in line with the argument that small firms tend to rely mainly on the knowledge of their CEOs and managers for developing innovation (Burton, 2001) as these leaders often consider their own activities as sufficient and rarely engage their employees in developing innovations. Nonetheless, we found significant results to indicate process innovation in small firms is promoted by the use of opportunity-enabling HR practices, while their organization innovation is promoted by the use of both opportunity-enabling and human-capital-enhancing HR practices. This seems to suggest that instead of relying solely on the expertise of CEOs and managers in the innovation process, soliciting employees' competencies and providing them with the opportunity to contribute may prove to have a positive effect on small firms' innovation performance (Andries and Czarnitzki, 2014). Meanwhile, unlike small firms, all the three HR components appear to be important for all the measured innovations in ***medium-large firms***, although on a contingent base. Specifically, OEH practices promote product innovation; HEH practices promote process and organization innovation; and MEH practices promote process innovation.

It is worth noting that **service firms** are similar to **medium-large firms** in terms of innovation performance that could be gained from the use of HRM practices. Indeed, both types of firms experience product innovation benefit from the OEH system, and organization innovation benefits from the HEH system. ***Manufacturing and small firms*** are also similar in regards to the innovation benefit that could be attained from the use of HRM practices. In particular, organization innovation in both groups of firms is promoted by the same set of HRM practices (i.e., OEH and HEH practices). Secondly, both ***Manufacturing and small firms*** do not experience significant product innovation impact from the use of HRM practices.

Contributions and implications

Theoretical contribution: This study offers a number of important theoretical contributions. First, we drew upon the behavioural perspective of HRM, human capital theory, and the resource-based view to demonstrate that HRM has a positive relationship with firm innovation, and thus extended previous models of HRM and organizational performance linkage (Gittell et al., 2010; Chang Lepak et al., 2012; Lee et al., 2019). Second, this current study contributes to the limited literature on the HRM and innovation relationship. While there is extensive research on the link between HRM and various indicators of firm performance such as productivity, employee turnover, firm growth and corporate financial performance (Batt and Colvin, 2011; Huselid and Becker, 2011; Jiang, Wang et al., 2012; Patel et al., 2013), little research attention has been paid to the potential influence of HRM on firm-level innovation. This study adopted the system approach to HRM and provided empirical evidence of a direct relationship between human-capital-enhancing HR practices, motivation-enabling HR practices and opportunity-enabling HR practices and innovation. Third, this study considered multiple innovation outcomes as well as the potential for different relationships with HRM systems. The empirical analysis revealed that HR system impact is contingent on type of innovation: different modes of firm innovation performance are associated with different combinations of HRM practices. For instance, opportunity-enabling HR practices were more effective for product and organization innovation; human-capital-enhancing HR practices were more effective for both process and organization innovation; and motivation-enabling HR practices were more appropriate for organization innovation. This finding is consistent with prior research suggesting that different components of HRM systems may have heterogeneous effect on specific organizational outcomes (e.g., Batt and Colvin, 2011; Gardner et al., 2011; Gong et al., 2009; Liao et al., 2009; Jiang, Lepak et al., 2012).

Analytical and methodological contribution: This study introduces a novel data match that allows us to contribute to the causal understanding of how HRM practices influence innovation outcomes, and to the limited literature on the HRM and innovation link. First, we develop a new data link between the UKIS and the ESS surveys in such a way that the timing of our HRM practices (obtained from the ESS survey) is between 1 - 3 years prior to an innovation outcome (obtained from the UKIS survey). Secondly, unlike most studies that rely on perceptual measures to gauge firm-level innovation (e.g., Ahmad and Schroeder, 2003; Andreeva et al., 2017; Lopez-Cabrales et al., 2009), our study uses some of the more preferred objective measures of innovation such as the introduction of new or significantly improved product, process or organization practices and/or strategies. This gives us the opportunity to provide robust evidence of the causal link between HEW systems and innovation.

Managerial or practice contribution. The exact HRM system that is instrumental to the development of innovation, particularly the attainment of different innovation aspirations under firm-specific context, has received little attention. In this study, we developed and tested the causal effect of three different HRM systems on three different innovation outcomes and across multiple firm-specific characteristics. The study revealed different innovation aspirations require different HR practices. It also revealed that the effect of HRM practices is contextual. For instance, if a firm seeks product innovation, then the OEH system would be more appropriate than the other HRM systems – especially if the firm is in the service industry or has 50 or more employees. Similarly, it would be more beneficial for firms looking to process innovation to adopt either the OEH system or the HEH system. Firms seeking innovation in business strategies and/or practices should consider either the HEH system or the MOH system, particular if firm is in the manufacturing industry or has less than 50 employees.

4.7 Limitations and future research

One limitation particular to this study is the use of large-scale secondary datasets. The analysis of large-scale database such as the UKIS and ESS presents several questions that cannot be fully investigated without more direct observational research methods. Such datasets do not offer in-depth knowledge about how firms make decisions in term of HRM adoptions for innovation performance. A greater knowledge is needed about how different innovation aspirations inform various HRM practices adoption. Indeed, it would be useful to develop a number of qualitative studies of how firms in different industries and/or of different sizes make strategic decisions about various HRM practices to reflect their innovation aspirations. Second, the study focussed on the distinction between product, process and organization innovations only. For this reason, it remains unclear how different innovation aspirations inform different HRM systems. Future research could use the same dataset to explore other innovation outcomes such as radical or incremental innovations, proportion of firm’s total sale that comes from new product or service, or measures of innovation success in terms of productivity and employment growth.

Chapter 5

5 Conclusion of thesis

Firms increasingly rely on public innovation supports for their innovation activities. Previous research on the effectiveness of public support often concentrates on analysis of individual policies (e.g., Arque-Castells and Mohnen, 2011; Czarnitzki and Hussinger, 2018; Sterlacchini and Venturini, 2019). This is despite the fact that firms often receive multiple public supports which interact with one another to create either a complementary, trade-offs or neutral effect. This has led to a call to researchers for analysis of the interaction effects of policy mixes that firms receive to avoid attributing the effect of other supports to individual supports (Flanagan et al., 2011; Rogge and Reichardt, 2016; Lenihan and Mulligan, 2018). Another argument put forth by this thesis is based on the fact that prior literature on public support impacts often considers either innovation input or innovation output additionality (e.g., Guerzoni and Raiteri, 2015; Marino et al., 2016; Freitas et al., 2017; Radas et al., 2015). This is despite the fact that any innovation input additionalities firms achieve from public support might not guarantee subsequent additionality in their innovation output. The third argument of this thesis concerns the limited research on how strategic human resource management (SHRM) impacts on firm innovation. This argument is predicated on the fact that there is a vast number of studies on the relationship between SHRM and other firm performance outcomes including productivity, corporate financial performance, and firm growth (e.g., Batt and Colvin, 2011; Huselid and Becker, 2011; Patel et al., 2013) with little attention to the SHRM and firm innovation link, although firms are increasingly relying on HRM practices to improve their innovation performance.

To fill these three research gaps, this thesis dwelt on the rich information in the UKIS and the ESS datasets to first offer analytical insights on the additionalities of the UK's R&D tax credits and R&D grants, and policy mix. Analytical consideration is also given to the effectiveness of the individual policies in isolation. Second, analysis of the effectiveness of public support is undertaken over both innovation input and two innovation outputs in terms of additionality in firms' internal R&D, product innovation and process innovation. Third, the thesis examined the importance of three distinct HRM systems for firm innovation. The conceptual argument of this part of the study is based on the AMO framework and assumes that HRM systems impact on firms' innovation by contributing to employees' competencies, motivating employees to dispense their competencies for productive role behaviours and by providing the opportunity for employees to participate in substantive decisions through the way that work is organised. This section of the thesis thus developed three different HR systems namely; human-capital enhancing HR (HEH) system, motivation enabling HR (MEH) system, and opportunity enabling HR (OEH) system, and subsequently examined their causal impact on three different innovation outcomes namely; product, process and organisation innovation.

This thesis examined external factors (policy initiatives) and internal factors (HRM systems) to firms and how they both enhance firms' capability for innovation activities. The motivation for examining HRM systems alongside public interventions is based on the fact that both factors are crucial drivers of innovation success due to their capacity to enhance firms' internal innovative capabilities. While this thesis did not examine the mediating effect of innovation capabilities for the HRM-innovation and policy-innovation link, prior literature provides empirical evidence of this relationship (Zhou et al., 2022).

5.1 Summary findings

5.1.1 Policy effect on R&D investment and innovation

The result from the research on R&D investment impact of public support indicates a hierarchy in impacts: tax-incentives-only has the highest impact, followed by policy mix and then grant-only. Indeed, the proportion of firms that engaged in internal R&D is 27 percentage points higher among firms that benefited from the policy mix than the control group of firms that did not receive any public support, confirming the general consensus in the literature that public funding stimulates additional private R&D efforts in beneficiary firms. On the other hand, the likelihood of declaring having engaged in internal R&D is 31.4 percentage points more among the proportion of firms that benefited from tax incentives only than their control group, and 13.2 percentage points more for firms that benefited from grant support than their control group. This seems to suggest that it is economically more beneficial for policy agents to concentrate on supporting firms through tax incentives only, since the resultant additionality effect is numerically higher than the effect of grant-only and policy mix supports. This result is supported by an earlier study favouring tax-incentives-only over policy mix and grant-only initiatives for achieving higher additionality in private R&D investment (Mulligan et al., 2017).

Meanwhile, the result from the output additionality effect seems to suggest that grant in isolation has no significant output additionalities effect, while tax incentives are associated with promoting output additionalities in participating firms. The additionality effect of tax incentives is particularly high for product innovation relative to process innovation. Also, there is a complementary effect of tax incentives on grants when the two policies interact. That is, the interaction of grant and tax incentives in a mix creates stronger additionality in both product and process innovations than those generated by tax incentives in isolation. A similar result was found by Berube and Mohnen (2009) who showed that about 80% of Canadian manufacturing firms that used a mix of tax credits and grants recorded having undertaken at least one innovation while about 72% did so among firms that used tax credit only support.

5.1.2 HRM practice effect on innovation

The marginal effect estimations from multiple logit models linking innovation to the various HR systems indicate a general positive and significant effect, although the effect on process and organisation innovations seems to be higher than the effect on product innovation. Specifically, while the use of opportunity-enabling system and human-capital-enhancing system respectively increases the likelihood of organisational innovation by about 9% and 13%, the use of human-capital-enhancing system and motivation-enabling systems respectively leads to about 9% and 12% increase in the likelihood of process innovation. The smallest effect of HRM is in respect of product innovation which is about 6% increase from the use of opportunity-enabling system. As most HRM practices are largely procedural and organisational, involving creative routines and creative ways of undertaking tasks, it is not surprising to observe higher effects of HRM practices on organisation and process innovation than observed for product innovation.

The concluding discussion of the thesis findings from this point will be a comparison of policy and HRM effect across the various performance measures. In view of this, readers can refer to estimates reported in Table 5A. It should be pointed out that Table 5A presents a consolidation of all the tables of result already included in Chapter (2 – 4) for the purpose of this current discussion.

It can be noted from the full sample results presented in Table 5A that the effect of policy initiatives on the likelihood of product innovation is approximately about 10% to 16% higher among participating firms, compared to a 6% increase from the use of HRM practices. Conversely, the effect of policy initiatives on process innovation is approximately about 6% to 11% compared to the effects of HRM practices which is approximately between 9% and 12%.

It is not surprising to observe a higher effect of targeted policy initiatives on product innovation since most of the UK's grants are particularly oriented towards new product development rather than process innovation. HRM practices on the other hand largely relate to how firms organise and execute their day-to-day jobs, hence the obvious higher effect on process innovation.

Table 5A: Consolidated results of thesis

5A1: Full samples

Public policy effect				HRM systems effect			
ATET	internal R&D	Product innovation	Process innovation	marginal effect	Product innovation	Process innovation	Organisation innovation
Policy mix	27.0	16.1	11.2	Human-capital-enhancing	(+)	8.77	12.83
Tax only	31.4	10.2	5.63	Motivation-enabling	(+)	12.23	(+)
Grant only	13.2	(+)	(+)	Opportunity enabling	5.82	(+)	8.97

5A2: Small (10 - 50 employment)

Public policy effect				HRM systems effect			
ATET	internal R&D	Product innovation	Process innovation	marginal effect	Product innovation	Process innovation	Organisation innovation
Policy mix	23.8	10.9	17.3	Human-capital-enhancing	(+)	(+)	17.18
Tax only	34.8	9.3	(+)	Motivation-enabling	(+)	(+)	(+)
Grant only	12.3	(+)	(+)	Opportunity-enabling	(+)	16.26	17.44

5A3: Medium-Large (50+ employment)

Public policy effect				HRM systems effect			
ATET	internal R&D	Product innovation	Process innovation	marginal effect	Product innovation	Process innovation	Organisation innovation
Policy mix	24.5	15.6	12.3	Human-capital-enhancing	(+)	12.01	13.48
Tax only	27.9	8.44	5.92	Motivation-enabling	(+)	17.09	(+)
Grant only	9.9	(+)	(+)	Opportunity-enabling	9.46	(-)	(+)

5A4: Manufacturing

Public policy effect				HRM systems effect			
ATET	internal R&D	Product innovation	Process innovation	marginal effect	Product innovation	Process innovation	Organisation innovation
Policy mix	20.2	16.7	(+)	Human-capital-enhancing	(+)	(+)	16.63
Tax only	23.6	10.3	9.53	Motivation-enabling	(+)	(-)	(+)
Grant only	(+)	(-)	(+)	Opportunity-enabling	(+)	(-)	14.78

5A5: Service

Public policy effect				HRM systems effect			
ATET	internal R&D	Product innovation	Process innovation	marginal effect	Product innovation	Process innovation	Organisation innovation
Policy mix	30.4	8.85	16.1	Human-capital-enhancing	(+)	(+)	8.6
Tax only	35.5	10.9	(+)	Motivation-enabling	(+)	(+)	(+)
Grant only	11.2	(-)	(-)	Opportunity-enabling	6.1	5.1	(+)

Notes: Only significant estimates are recorded.
(+) represents insignificant positive; (-) represents insignificant negative

Table 5B: Consolidated results of thesis (Continued)

	High-tech manufacturing			Low-tech manufacturing		
ATET	Internal R&D	Product innovation	Process innovation	Internal R&D	Product innovation	Process innovation
Policy mix	11.3	20.4	(+)	36.4	25.8	(-)
Tax only	19.5	12.3	14	26.4	(+)	(+)
Grant only	(-)	(-)	(+)	29.6	(+)	25.5
	Knowledge intensive service			**Less knowledge intensive service**		
ATET	Internal R&D	Product innovation	Process innovation	Internal R&D	Product innovation	Process innovation
Policy mix	28.8	10.7	15.7	34.6	(+)	(+)
Tax only	32.6	9.62	8.33	47.9	12.6	(+)
Grant only	13.4	(-)	(-)	(+)	18.9	(+)
	1st productivity frontier			**2nd productivity frontier**		
ATET	Internal R&D	Product innovation	Process innovation	Internal R&D	Product innovation	Process innovation
Policy mix	0.0456	(-)	(+)	0.151	0.295	(+)
Tax only	0.0305	(-)	(+)	0.32	0.16	(+)
Grant only	0.078	(+)	(-)	(+)	(-)	(+)
	3rd productivity frontier			**4th productivity frontier**		
ATET	Internal R&D	Product innovation	Process innovation	Internal R&D	Product innovation	Process innovation
Policy mix	0.242	0.152	(+)	0.155	0.181	(+)
Tax only	0.294	0.193	0.0724	0.266	0.132	0.0956
Grant only	(+)	(-)	(-)	(+)	(-)	(+)

Notes: Only significant estimates are recorded.
(+) represents insignificant positive; (-) represents insignificant negative

5.1.3 Firm heterogeneity across policy effect and HRM effect

The thesis also explored whether there are differentials in the innovation benefits of public support and HRM practices across multiple firm-specific characteristics including size, industries, degree of technology and knowledge intensity. As already explained in both Chapter 2 and Chapter 3, the input additionality (i.e., internal R&D) and output additionalities are respectively interpreted as the percentage increase in the proportion of treated firms that are likely to engage in internal R&D, and proportion of treated firms that are likely to introduce product and process innovation in comparison with the control group of firms that receive no public support. The research evidence suggests that the effect of the targeted policies on the propensity to engage in internal R&D is strongest with the use of tax-incentives-only (between 3% and 48% points), followed by policy mix (between 5% and 36% points), and then grant-only (between 8% and 30% points). The effect pattern is consistent across all the considered firm-specific types, except for firms in the lowest quartile of the productivity distribution who register their strongest input additionality from participation in grant-only. In fact, the input additionality that the least productive treated firms obtained from participating in grant-only (about 8% points) is about three time the effect from the use of tax-incentives-only (3% points) and about twice the effect they derived from the use of policy mix (about 5% points) (see Table 5B). It is also worthy of note that grants work better for low productivity firms compared to tax incentives which work better for higher productivity firms.

Meanwhile, low-tech manufacturing companies experienced the largest input additionality for participating in grant-only and policy mix supports. Indeed, the low-tech manufacturing firms that participated in grant-only or policy mix are respectively 30 and 36 percentage points more likely to declare having engaged in internal R&D than their respective untreated counterparts. And the LKIS in the sample seems to experience the largest input additionality in respect of the use of tax-incentives only, registering 48% points more likely to engage in R&D (see Table 5B).

5.1.3.1 Policy and HRM effect across size

Interesting patterns are observed when the effects of policy initiatives and that of HRM practices are compared across the various firm characteristics. First, innovation among ***small firms*** appears to benefit more from participating in policy initiatives than from the use of HRM practices. In fact, HRM practices seem to be not important for product innovation in small firms, but they are important for their process and organisation innovations. Participating small firms in the research sample experienced the highest input additionality from participating in tax-incentives-only (34.8% points), followed by policy mix (23.8% point) and then grant-only (12.3% points). Indeed, the analysis seems to suggest that the input additionality that small firms gained by participating in tax-incentives-only is about three times the benefit they gained from participating in grant-only support, as they registered about 35% points benefit from participating in tax-incentives-only compared to 12% points gain from participating in grant-only (Table 5A2, column 2). Surprisingly, there is no significant evidence to suggest that grant-only promoted additional innovation among participating small firms. Policy mix on the other hand offered high innovation performance impact as participating small firms registered about 11% and 17% additionality respectively for product and process innovation (Table 5A2, columns 3 & 4).

Meanwhile, there was no significant product innovation gain from the use of HRM practices by small firms, but they experienced process and organisation innovation benefit since small firms in the sample registered between 16% and 17% more likelihood of innovation. These findings in summary seem to suggest that while the internal R&D performance of small firms is at its highest with the use of tax-incentives-only, their innovation output performances (both product and process) are highest with the use of policy mix. Secondly, HRM practices do not significantly promote product innovation in small firms, but they do promote their process innovation particularly with the use of the opportunity-enabling system.

In general, there seems to be not much difference between the innovation benefits that ***medium-large firms*** experienced from participating in policy initiatives compared with the adoption of HRM practices. One exception is product innovation in which the impact that focal firms experienced from participating in policy initiates is twice the impact they experienced from using HRM practices. Indeed, for participating medium-large firms in the research sample, the use of policy mix increases the probability of product innovation by about 16% while the probability of product innovation goes up by only 9% with the use of HRM practices.
Unlike small firms where HRM appears to have no significant impact on product innovation, HRM practices appear to be very important for both product and process innovation in medium-large firms. Indeed, medium-large firms experience approximately between 10% and 17% performance gain in respect of product and process innovation with HRM practice adoption. In summary, the findings seem to suggest that, like small firms, the internal R&D performance in medium-large firms is highest with the use of tax-incentives-only while their innovations (both product and process innovations) benefit most with participation in policy mix. Secondly, unlike small firms, all innovations considered in this study relating to medium-large firms are promoted by the use of HRM practices.

5.1.3.2 Policy and HRM effects across industry

Innovation among ***manufacturing firms*** is promoted only by participation in policy initiatives, except for organisation innovation in which HRM practices seem to be important. That is, while manufacturing firms experienced significantly high organisation innovation performance from the use of HRM practices, they experienced significant product and process innovations performance only by participating in public innovation supports, with participating firms registering approximately between 10% and 17% additionalities across product and process innovations. HRM practices on the other hand are very important for organisation innovation in manufacturing firms as participating firms registered approximately between 15% and 17% increase in probability of innovation. Secondly, grant-only seems to offer no significant effect on either internal R&D or innovation in manufacturing firms. Tax-incentives-only initiatives are very important for internal R&D and all innovations among manufacturing firms as participating firms register about 24% additionality in internal R&D and up to 10% additionalities in innovations. Policy mix on the other hand offers the highest additionality on product innovation (about 17% points) although at the expense of no significant process innovation effect and lower impact on R&D investment than could be achieve with tax-incentives-only.

Manufacturing firms and small firms are similar in regards to the innovation benefit that could be attained from the use of HRM practices. In particular, organisation innovation in both groups of firms is promoted by the same set of HRM systems (i.e., HEH and OEH consisting of team-work on projects, task variety, task discretion, flexible working, quality employee identification recruitment processes and on- or off- the-job training). Also, both groups of firms do not experience significant product innovation impact from the use of HRM practices (although small firms do get process innovation impact from HRM practices).

Similar to small firms, innovation in ***service firms*** benefits more from policy initiatives than from HRM practices (Table 5A5, column: 3, 4, 6 & 7). In fact, the impact of public policy on innovation in service firms is about three times the innovation gain they experience from the use of HR systems. Similar to the other types of firms, service firms participating in public supports experienced the highest input additionality from tax-incentives-only support (36%), followed by policy mix (30%) and then from grant-only supports (11%). Indeed, the analysis seems to suggest that the internal R&D performance that service firms experienced by participating in tax-incentives-only is more than three times the benefit they experienced from participating in grant-only support, as they registered about 36% benefit from participating in tax-incentives-only compared to a 11% gain from participating in policy grant-only (Table 5A5, column 2). There is no significant evidence to suggest that grants promote additional innovation output among participating service firms in the study’s sample. Policy mix offers the highest innovation impact relative to tax-incentives and grants in isolation, and in particular with regards to process innovation (about 16% in additionality).

While service firms are similar to small firms in terms of performance gains that could be obtained from participating in policy initiatives, they are otherwise similar to medium-large firms in terms of innovation performance that could be gained from the use of HRM practices. Indeed, both types of firms experience product innovation benefit from the opportunity enabling HR system, and organisation innovation benefit from the human-capital enhancing HR system.

Grant-only appears to offer no significant effect on either internal R&D or innovation in ***high-tech-manufacturing*** firms. Tax-incentives-only initiatives are very important for internal R&D and all innovations among high-tech-manufacturing firms as participating firms register about 20% additionality in internal R&D and up to 14% additionalities in innovations. Policy mix on the other hand offers the highest additionality on product innovation (about 20%) although at the expense of no significant process innovation effect and lower impact on R&D investment than could be achieve with tax-incentives-only. Meanwhile, ***Low-tech manufacturing*** experience similar innovation performance from policy mix and grant-only supports. Finally, Policy mix offers the highest innovation performance gain in KIS, while participating LKIS experience their highest innovation performance from tax-incentives-only support.

5.2 Contribution of thesis

This thesis offers a number of important theoretical contributions. The framework used in the two policy mix studies allowed for the analysis of the importance of tax-incentives-only, grant-only and their interaction (policy mix) for both R&D input and innovation output. By developing and examining both R&D input and innovation output effects of the three distinct policy initiatives, this thesis extends our understanding of the innovation performance of public support in a number of ways. First, it allows for a deeper understanding of the impact of policy mix on both R&D and innovation. Multiple dimensions of policy initiatives as well as the potential for different effects on innovation outcomes are examined. Researchers have called for the need to simultaneously examine both the innovation input and innovation output effects of innovation supports since the fact that public support may induce beneficiary firms to increase their innovation input does not necessarily imply that any such increase in input effort will automatically translate into commercial innovation output (Czarnitzki et al., 2011; Freitas et al., 2017). Moreover, different forms of policy initiatives may lead to heterogeneous input and output effects. Much of the literature on the effectiveness of public policy support has examined the effects of individual policies on either innovation input outcomes (e.g., Sterlacchini and Ventuini, 2019; Czarnitzki and Lopes-Bento, 2013) or innovation output outcomes (e.g., Cappelen et al., 2012; Bronzini and Piselli, 2016). There is another stream of studies, although small, that considers both the innovation input and innovation output effects of policy supports, but their analyses consider individual policies in isolation and do not pay attention to the potential interaction effect when instruments mix with one another (e.g., Freitax et al., 2017; Czarnitzki and Hussinger, 2017. There is yet another stream of studies, although very limited, which evaluates the effect of individual policies as well as policy mix, but does so for either innovation input only (e.g., Guerzoni and Raiteri, 2015; Reichardt and Rogge, 2016; Marino et al., 2016; Pless, 2020) or innovation output only (e.g. Bérubé and Mohnen, 2009). Guerzoni and Raiteri (2015) specifically examined the effect of tax credits and grants in isolation as well as their interactions on private R&D input. Although the authors found no significant input additionality of tax credits or grants in isolation, they found a significantly positive effect when the two supports interact. Reichardt and Rogge (2016) also provided in-depth insight into the innovation effect of policy mix as well as their characteristics in terms of their consistency. However, their study does not examine the implications of policy mix effect for different types of firms.

To the best of my knowledge this current study is the only one that simultaneously examines the effects of both individual instruments in isolation and policy mixes across both innovation input and innovation output outcomes. With the help of the UKIS dataset which provides information on firms that received R&D tax incentives and/or R&D grants as well as information on multiple firm innovation input and innovation output outcomes variables, this current study tested the effectiveness of public support and provided empirical support for the theoretical proposition that public innovation support (either administered in isolation or in a mix) leads to additionalities in innovation input and innovation output outcomes. This is consistent with prior research suggesting that public policies promote firm innovation performance (Czarnitzki and Lopes-Bento, 2013; Marino et al., 2016; Freitas et al., 2017). By examining the effects R&D tax incentives and R&D grants in isolation as well as their interaction effects cross innovation input and output outcomes, this study offers new insight and a deeper understanding of the heterogeneous effect of different public support initiatives across the different innovation outcomes.

A further contribution to the literature is the fact that the current thesis introduced a novel data match that allowed contribution to the causal understanding of how HRM systems influence innovation outcomes, and to the limited literature on the HRM and innovation link. Studies that examine the link between HRM systems and firm innovation only conclude an association between the use of strategic HRM systems and higher levels of innovation, with few to none establishing a causal link. This thesis offers evidence of a causal link between HR systems and firm innovation and thus extends the literature.

One novel aspect of the thesis is the consideration of multiple innovation indicators, and the provision of insight into the differing effect of the various policy treatments and HR systems across multiple firm characteristics such as size, industry, and technology intensity as well as productivity frontiers. The results suggest the extent of relationship between public support and firm performance is contingent on the type of policy initiative, the type of firm performance measured, and the firm-specific context. The results also suggest differential effects of the three components of the AMO framework (i.e., HR systems). This finding is important both in theory and in the methodology of measuring the AMO components. Theoretically, the finding challenges previous research, in which the assumption has been that all the components of the AMO framework should function together. Our findings provide a reminder to researchers that different recipe from the AMO menu may be needed depending on the specific context of firms.

5.3 Policy and practice implications

5.3.1 Policy implications

The policy implication of the evidence from the public policy and innovation input study appears to suggest that the best-performing public policy is tax incentives, followed by a mix of tax incentives and grants. Grants in isolation seem to be the least effective in stimulating private expenditure in R&D. The relatively higher performance of tax incentives is not surprising since the UK's indirect support for firm-level R&D dominates direct support. Furthermore, in comparison with grant-only, tax-incentives-only is more effective in spurring both product and process innovation in treated firms. The effectiveness of tax incentives only is more pronounced particularly for product innovation irrespective of firm size, industry, technology or knowledge intensity level, and firm productivity level. Again, a mix of tax incentives and grant supports provide enhanced innovation additionalities compared to the individual supports in isolation, particularly for product innovation in manufacturing (both high-tech and low-tech), KIS firms, small and medium-large firms.

Firms respond differently to policy initiatives depending on their individual-specific characteristics. That is, under some circumstances, tax incentives may be more effective than grants or policy mix in stimulating private investment in innovation activities. And under other circumstances, policy mix may be more effective than grants. This thesis thus provides recommendations for policy agents looking to design support schemes targeted at boosting innovative activities in specific type of firms. First, the evidence from this research suggests that small firms and service firms show similar performance behaviour towards public support. The impact results suggest that policy makers seeking to achieve the highest input additionality in such firms should consider tax-incentives-only. However, if the objective is to achieve additionality in both product and process innovation, then the evidence suggests policy mix as the best option and the only option in the case of process innovation. Second, innovation among medium-large firms (both product and process) responds best to policy mix since participation firms gained twice the impact they experienced from tax-incentives only. Their internal R&D however, responds best with participation in tax-incentives-only. Third, policy agents seeking to boost innovation in manufacturing firms can choose between tax-incentives-only and policy mix initiatives. While tax-incentives-only offers very strong input (about 24%) and output additionalities (approximately between 10% and 11), the highest additionality in product innovation could be attained with policy mix (about 17%) although at the expense of no significant process innovation effect. Fourth, with tax-incentives-only, policy makers can achieve significantly high impact on both R&D investment and innovation in high-tech firms. However, if the objective is to achieve the highest impact on new product development, then the best option is policy mix, whose high impact also comes at a cost of no significant effect on process innovation and a lower effect on R&D than the effect tax-incentives-only could offer. Fifth, for low-tech manufacturing, policy makers can choose either policy mix or grant-only initiatives. Finally, policy mix is the most important support for innovative performance in KIS, while tax-incentives-only is the most important for LKIS.

5.3.2 Practice implications

As part of the evaluation process, this thesis developed and tested the causal effect of three different HRM systems on product process and organisation innovation, and the evidence provides insight into the fact that different innovation aspirations require different HRM systems. The estimated impacts suggest that alternative strategic HRM systems are contingent on the type of innovation. It is therefore recommended that managers adopt a contingent approach to HRM practice adoption. For instance, there is no significant evidence that HRM practices promote product innovation in small firm. On the other hand, both process and organisation innovations can be achieved with the use of HEH HR system and OEH HR system. Second, Managers of medium-large firms with product innovation aspirations should consider HR practices such as team-work on projects, task variety, task discretion and flexible working (i.e., OEH system). Managers seeking organisation innovation can consider adopting either quality employee identification recruitment processes or employee training (i.e., HEH system). Using either opportunity enabling system or human-capital enhancing system significantly increases the chances of process innovation in medium-large firms. Third, the results seem to suggest that manufacturing firms can experience significant innovation benefit from the use of HRM only in regards to organisation innovation, and for that manager should concentrate on human-capital enhancing system. Finally, by adopting either human-capital enhancing system or opportunity enabling system, managers of service firms can achieve innovation in product, process and organisation.

5.4 Limitations and future research

A particular limitation of this study is the use of large-scale secondary datasets. The analysis of large-scale database such as the UKIS and ESS presents several questions that cannot be investigated without more direct observational research methods. First, a much greater insight is needed about how firms make strategic decisions in terms of project investment selections and policy participation Similarly, a greater in-depth knowledge is needed about how different innovation aspirations inform various HRM practices adoption by specific firms. Most of the studies on both public support and HRM practices are based on secondary data and infer relationship from data and existing theoretical models. It would be useful to develop a number of qualitative studies of how different firms make their R&D investment and policy participation and HRM practices adoption decisions. In-depth case study and observational research may allow a worthwhile description of how firms may decide whether or not to substitute their own R&D investment with government funding, and the reasons why firms' investments in R&D may or may not translate into innovation output.

This study also faces some methodical limitations. First, it is focussed on the distinction between product, process, and organisation innovations only. For this reason, it remains unclear how different innovation and performance strategies inform a firm's decision to participate in a particular policy intervention or to employ the use of HRM practices. Future research could use the same dataset to explore other innovation outcomes such as radical or incremental innovations, the proportion of a firm's total sale that comes from new product or service, or measures of innovation success in terms of productivity and employment growth. Second, grant-only was found to be significant for R&D investment but insignificant for the two innovation output outcomes. There is the possibility that firms are still undertaking experimental developments to validate their new and improved products and/or processes. Due to the limitations of my data, this research did not examine the effect of policy support, particularly grant-only, on firms' experimental developments. Future research is needed to understand the effect of grant support on the different stages of firms' innovation development. Third, this research used firms that did not receive any public support as the counterfactual for policy mix participation. This approach does not directly examine how policy mix performs vis-à-vis tax incentives and grants in isolation. Future research could extend this research by using participation in tax-incentive-only and grant-only supports as two distinct control groups for participation in a mix of both supports. Fourth, a future research challenge is to understand changes in firms' participation in public interventions over time. The approach taken by this current study focused on public supports and their additionality effects in one period. However, with future innovation surveys, it will be possible to examine whether the support participation patterns of firms has changed over time and the resultant effect on R&D investment and innovation. Indeed, it will be interesting to explore whether changes in R&D and innovation performance of industries and/or across firm sizes are reflected by changes in the participation patterns of individual firms. A longitudinal evaluation may be better at capturing the dynamic aspects of policy support.

This study also faces some analytical limitations. Lack of information on the amount of support that firms receive precludes the evaluation of how different levels or intensity of public support may impact firm innovativeness. This remains a critical challenge since at the moment, it is unclear exactly how much public support is enough to achieve a socially desirable outcome. Exploring administrative data on the amount of tax incentives and direct R&D supports that are available to firms may help with the analysis of when government may be under- or over-subsidising.

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